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TECHNICAL REPORT

CHARACTERIZATION OF FOREST VEGETATION ANALOGS

By: Rodger A. Brown, George E. McVehil
Robert L. Peace, Jr., and Robert W. Coakley

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Deseret Test Center
Fort Douglas, Utah

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I. SUMMARY

All forests, regardless of their individual characteristics, modify the free-atmosphere wind, stability, and turbulence conditions to create a local environment within and above the trees that differs substantially in its diffusion characteristics from that which would be present in the absence of trees. It has been the purpose of this study to characterize these forest influences and to develop a forest classification system, based on diffusion effects, that can be used to discriminate between forests with different diffusion properties.

In order to classify the basic influences of a forest, an attempt has been made to delineate the significant features of diffusion which are influenced by forest characteristics and associated meteorological conditions. Of the various factors that determine diffusion in a forest environment, this study has indicated that vertical transport of material or momentum through the canopy and in the boundary layer above the forest is the most important and is strongly controlled by forest type. The vertical transport of material is a consequence of both the physical structure of the canopy (namely, canopy roughness, closure and density) and of the ambient meteorological conditions above the canopy (stability and wind velocity).

The first phase of this study involved an investigation of gross forest influences that might be reflected in diffusion and meteorological measurements made in a variety of forests. Data from diffusion and munition tests in forest environments were analyzed in an effort to delineate differences in diffusion properties, particularly vertical diffusion, between forests of different physical characteristics. Significant variations in vertical transfer rate were found, using results published in ORG Note 29 (86). The Note applied theoretical models, together with dosage (fluorescent particles) and meteorological measurements in four different types of forests (tropical rain

forest, jungle, deciduous-summer, and deciduous-winter), to solve for canopy ventilation rate. By making use of the tabulated ventilation rate information, it was established in the present study that, for any given stability and above-canopy wind, ventilation rate is approximately a linear function of the ratio of below-canopy wind speed to above-canopy wind speed. This result appears to be generally valid for all forest types included in the data. It can therefore be concluded that the vertical transfer of momentum through the canopy (as reflected by the wind speed ratio) behaves in the same way as the vertical transfer of mass (as reflected in the ventilation rate, which was based on above- and below-canopy dosage measurements). Thus, the wind speed ratio can be used as a quantitative measure of the forest influence, since it responds completely to the physical effects of the vegetation in retarding vertical transfer.

Above-canopy wind speeds for various forests were plotted as a function of the below-canopy wind speeds (in a given above-canopy stability condition). The resulting families of curves indicate that steeper slopes are associated with the denser canopies. Thus, an index of the effect of the forest on vertical transfer (which has been called the Environmental Index) can be based upon the ratio of wind speeds. The Environmental Index is defined as the ratio of above- to below-canopy wind speed for the unique conditions of neutral above-canopy stability (Richardson number equal to zero) and an above-canopy wind speed of 5 m sec^{-1}. This definition of Environmental Index states, in effect, that for given above-canopy wind speed and stability, the below-canopy wind speed is a measure of the retarding influence of the canopy's physical structure on momentum transfer.

The second major emphasis in this study was given to developing techniques for characterizing the significant properties of a forest (from the standpoint of aerosol diffusion) on the basis of relatively simple physical forest measurements. The results described above, theoretical analysis, and diffusion tests from a number of locations all indicate that the roughness and closure of the forest canopy are instrumental in determining vertical transfer rates. Therefore, an investigation and trial application of statistical approaches that could be used to relate canopy height measurements to the roughness and closure of the canopy were carried out. A section of forest

canopy in Thailand, for which aerial photographs were readily available, was used to test several statistical approaches. The test results indicate that a method based on measurementsof canopy height made along a line can provide quantitative characterization of a forest canopy. The characterization is based on two quantities--β and μ--both of which are expressed as functions of height above the ground. β is defined as the fraction of the length of a straight horizontal line (at a given height) which is below the canopy profile; μ is defined as the number of times per unit length that the line crosses the profile. Closure information is determined from the β curve and roughness information is contained in both the β and μ curves.

To provide a forest index of general applicability, which can be derived from relatively accessible forest measurements, it will be necessary to refine and extend the relationships given in this report between wind ratio and forest type, using quantitative forest parameters in place of qualitative labels. Given quantitative relationships between, say, β or μ and wind ratio, the Environmental Index can be determined from aerial photographic data. It has not been feasible within the present study to define the exact relationship between β and μ curves and meteorological or diffusion parameters. Both canopy and meteorological measurements are required from a variety of forests and diverse meteorological conditions before the interrelationship of forest parameters and wind speed ratio can be firmly established. Note, however, that it is not necessary to make diffusion measurements. It has been suggested that an air-borne laser radar--instead of aerial photogrammetry--could be used to measure the β and μ parameters; in addition to providing real-time results, canopy density information also could be estimated from the laser measurements.

It is recommended that diffusion tests be run in at least five forests having widely varying physical characteristics. Five tests are believed to represent a minimum number needed to satisfactorily separate forest and meteorological influences. These tests would be used as a check on the validity of the Environmental Index determined from meteorological and diffusion measurements in the present analysis. At the same time, they

would provide the data required to define, at least in a preliminary form, the relationships between Environmental Index and statistical properties of a forest determined from photographic or radar data. The recommendations also include discussions of diffusion, forest, and meteorological measurements required for the experiments.

II. AEROSOL DIFFUSION IN THE FOREST

The objectives of the present study have been to characterize forest influences on aerosol diffusion, and to develop a forest classification system based upon these influences. An extensive literature survey has been conducted in order to summarize the information available from past research and field diffusion tests. Relevant background on meteorological effects of forests derived from this survey is presented in Appendix A. Those unfamiliar with the subject should read Appendix A before proceeding. Before discussing field test results and related forest characteristics, an outline of general diffusion problems and their relationship to forest properties is given in this Chapter. This outline provides a basis for the approach that has been taken, and the recommendations for development of a classification scheme presented later in the report.

A number of parameters defined by the aerosol concentration field as a function of time and space are conventionally used to characterize diffusion and transport of material in the atmosphere. The most frequently used parameters are dosage (time integral of concentration at a point), standard deviations of the spatial distribution of material in crosswind and vertical directions, and crosswind integrated dosage. These parameters, normally used in the analysis of munition tests, are not necessarily appropriate for characterizing diffusion processes in a forest environment. Most of the routinely applied parameters have well-defined interpretations in terms of diffusion rates only when the distribution of material is known, or can at least be assumed to be well-behaved (for example, a Gaussian distribution of material in space).

In a forest environment, there is usually a discontinuous, or at least highly variable, distribution of wind, temperature, and turbulence through the volume of interest. Accordingly, diffusing material may behave quite differently in different regions (for example, such regions as above-

canopy, in the forest canopy, in the trunk space, and in undergrowth). It is clear that models and cloud parameters based on uniform distributions and homogeneous turbulence fields usually will not be applicable. Since the concern here is with those features of aerosol transport that are most sensitive to the presence of a forest, or to differences between forests, it is essential that appropriate measures of cloud behavior be utilized. For the development of a forest analog classification, the emphasis should not be placed on applicability or details of cloud transport models as such. Rather, a description of the gross effects on turbulent diffusion and cloud transport produced by vegetation is sought. In order to define these gross effects and suggest appropriate measures of forest influence, we have attempted to summarize the diffusion processes of importance. The following section presents this summary. From it, conclusions on the most important forest effects and related forest properties are drawn.

A. Transport and Diffusion Processes Influenced by the Forest

The following outline has been compiled from study and analysis of test data, from knowledge of meteorological effects of vegetation, and from physical reasoning. It is not all-inclusive, but is intended to summarize what appear to be the most important cloud diffusion and transport effects produced by a forest.

1. Diffusion in the layer above the forest. Rates of turbulent diffusion above the canopy are determined by the scale and intensity of the turbulent wind components. These are strongly influenced by the character of the canopy irregularity and ambient meteorological conditions.

2. Diffusion through the forest crown. Turbulence characteristics can be expected to vary drastically through the region from above to below the tree crowns. The crowns can in effect represent a discontinuity or sharp gradient in the diffusion regime, and a physical barrier to vertical flux of aerosol. Therefore, transport into the forest from the clear space above the trees is one of the quantities of importance in defining forest effects.

3. Spatial variability in transport through the crown. The sizes of openings in nearly any forest crown vary over a wide range, and crown coverage must be expected to be nonhomogeneous on some scales. Accordingly, vertical motions and aerosol flux can be expected to vary in space. For different forests the pattern of variability may be different and the relative importance of large and small openings will vary. Thus, in addition to the mean diffusion rate through forest crowns, the variability of vertical flux will also be important and is likely to be an identifiable characteristic of different forest types.

4. Mean motion of a cloud in the forest. The average wind speed and direction in a forest inevitably are much different from the values outside. Since the mean wind is frequently variable in both time and space, the conventional model of a cloud moving in a straight line at constant speed is rarely if ever valid. To predict diffusion beneath the canopy, one needs information on the magnitude, direction, and steadiness of short-term mean wind in the forest.

5. Rate of spread of cloud or plume in the forest. Because the turbulence environment in a forest is not a function solely of meteorological conditions and is different from that in the open, knowledge is needed on rates of turbulent diffusion beneath the canopy. These will be influenced by density of undergrowth (horizontal permeability) and the processes by which turbulence and mean motion are transmitted into the forest from outside (canopy permeability).

6. Characteristics of flow at a forest interface. Many practical cloud transport problems involve the transport of material into a forest from outside, or across a boundary between two different forest regimes. Anomalous flow patterns may be set up at such places, and knowledge of the streamlines of mean flow and the turbulence regime within the forest edge is essential for treating these problems.

B. Diffusion, Meteorological, and Forest Parameters

If it is accepted that the above six general problem statements encompass the primary areas of concern related to aerosol dispersion in a forest environment, we can proceed to list the cloud properties, meteorological variables, and forest characteristics that are most pertinent to each problem. In the outline below, a set of variables is associated with each of the six problems. The first set of variables listed under each problem are aerosol distribution parameters, to be determined by measurement of concentration or dosage. The second set are meteorological parameters that must be known to separate ambient meteorological influences from forest influences. The third set of variables, given only in descriptive terms at this point, are the forest characteristics believed to be most closely related to the problem.

Problem 1: Diffusion above the canopy

Cloud Properties - Standard deviations of the space distribution of cloud material, and the maximum dosage, as functions of downwind distance.

Meteorological Properties - Vertical temperature gradient, mean wind speed profile, and intensity of turbulence, all above the canopy.

Forest Properties - Closure of canopy, roughness of canopy top, density of canopy vegetation.

Problem 2: Diffusion through the canopy

Cloud - Penetration rate, concentration and dosage versus time above and below canopy.

Meteorological - Wind speed above canopy, vertical temperature gradient above and below forest crown, turbulence intensity at canopy level.

Forest - Canopy closure, density, and thickness.

Problem 3: Space variability of vertical transport

Cloud - time and space variation in concentration and dosage fields below canopy.

Meteorological - Space variability in the vertical temperature gradient and standard deviation of vertical velocity at canopy level, above, and below.

Forest - Space variability in canopy height, closure, and density.

Problem 4: Cloud motion in forest

Cloud - Concentration or short period dosage as functions of time and space.

Meteorological - Mean wind velocity (averaging time $\sim$ 30 sec) in forest, wind velocity above forest, temperature gradient below and above canopy top.

Forest - Canopy density, undergrowth density, presence of openings or clearings.

Problem 5: Cloud spread in forest

Cloud - Cloud dimensions as function of time, area-dosage relationship

Meteorological - Turbulence intensity, scale of turbulence, mean wind and temperature profiles.

Forest - Undergrowth density, characteristic sizes of obstacles to flow, canopy closure.

Problem 6: Interface flow (stand border)

Cloud - Dosage field on both sides of interface.

Meteorological - Wind speed (outside and inside forest), vertical temperature gradient (outside and inside forest).

Forest - Density, vertical and horizontal distribution of density.

C. The Significance of Vertical Transport

Inspection of the preceding outline reveals that a majority of the physical problems are primarily dependent on vertical transfer of material or momentum in the boundary layer above the forest and through the canopy

itself. Problems number 1, 2, and 3 relate directly to these vertical transfers; problems 4 and 5 are concerned with wind and turbulence within the forest, but these depend most directly on the transfer of momentum and turbulent energy downward from above, and only secondarily on modification of properties by the lower vegetation or flow induced by below-canopy forces.

Since the central problem in characterizing forest effects appears to be specification of vertical transfer and its dependence on forest characteristics, any analog classification system must place primary emphasis on discrimination of vertical transfer properties or, as expressed in Appendix A, "vertical permeability" of the forest. Reference to the outline in Section B indicates that roughness, closure and density of the canopy top appear as significant forest properties in all problems related to vertical transfer, and indeed, for virtually all of the problems listed. It has been concluded therefore, that the most important diffusion property is the vertical transfer rate, and that the associated forest properties are the roughness, closure and density of the canopy. These diffusion and forest characteristics must form the basis of any classification method.

The fundamental hypothesis of the approach taken in this report is that gross aerosol transport effects of forests can be encompassed by classifying their vertical transfer properties. Analyses have, therefore, been directed toward showing the variation in vertical transfer in forests of different types and delineating the modifying effects of ambient meteorological conditions. On the basis of results from these analyses, a simple meteorological index of vertical transfer has been developed, and techniques for inferring vertical transfer properties from physical data on forest structure have been explored.

The following chapter considers, from a theoretical viewpoint, the effects of forest structure on vertical transfer. Following chapters then treat evidence of relationships from test results and proposed methods for determining pertinent forest characteristics.

III. FOREST CANOPY EFFECTS ON VERTICAL TRANSPORT

An extensive area of forest presents a rough, permeable surface over which the atmosphere moves. The effects of this surface can, for present purposes, be divided into two kinds: those effects, due primarily to the geometry of the canopy top, on air flow in the boundary layer above the canopy; and those effects on vertical transfer through the canopy and diffusion beneath. In the following these two sets of influences are explored with a view toward delineating the forest properties that are instrumental in controlling diffusion.

A. Aerodynamic Roughness

First, consider the role of geometry of the canopy top in determining wind structure and turbulent transfer above the canopy. The "aerodynamic roughness" of a surface is conventionally defined by a roughness length, z_o, which can be determined from analysis of the mean velocity profile above the surface. The velocity profile for neutral stability can be expressed as (Sutton (88)):

$$\overline{u} = \frac{u_*}{k} \ln \frac{z-d}{z_o} \qquad (3\text{-}1)$$

where $\overline{u}$ is mean wind speed, u_* is the friction velocity $(\tau/\rho)^{1/2}$, k is von Karman's constant = 0.4, z is height, τ is horizontal shearing stress (assumed constant through the layer where Eq. (3-1) applies), and ρ is density. The quantity d is a zero-plane displacement which has been found empirically to be required for application to very rough surfaces such as tall crops or forests. The zero-plane displacement can be considered to roughly represent the depth of "trapped air" in the forest; it can be seen from Eq. (3-1) that $\overline{u} = o$ where $z = d + z_o$. Clearly, the equation is applicable only for $z \geq d + z_o$.

The two variables that depend on the characteristics of the surface are z_o and d. As already noted, d merely represents an adjustment in the zero point of the height scale; z_o on the other hand enters the equations as a scaling factor for height. A given wind speed or turbulent exchange coefficient will occur at different absolute heights over different surfaces, depending on the appropriate z_o values for the surfaces. There are no direct methods known for determining z_o or d from measurements of the vegetation characteristics. However, some general rules for rough estimation are often quoted. Several authors, for example Paeschke (68), have taken d equal to the mean height of the roughness elements (grass blades, etc.). The roughness length is usually of the order of one-tenth the mean height of the elements. Kung (54) determined an empirical expression

$$\log_{10} z_o = -1.24 + 1.19 \log_{10} h \qquad (3\text{-}2)$$

where h is plant height in cm. Table I lists typical values of z_o and d for a variety of surfaces as calculated by various authors from observed wind profiles.

Table I

Zero-plane Displacement and Roughness Length for Various Natural Surfaces

Type of Surface	d(cm)	z_o (cm)	Source
Short grass (5-10 cm)	12	0.4	Davidson & Lettau (25)
Tall grass (50 cm)		9.0	Sutton (88)
Brush and small trees		30-70	Fichtl (32)
Small trees		30-100+	Webb (97)
Deciduous forest, 8-10 m			
bare of leaves	115	105	Lenschow and Johnson (57)
leafed	350	160	
Larch forest, 10 m	635	112	Allen (2)

Insufficient data are available to give representative values of d and z_o for a variety of forest types. However, the likely range of values to be encountered can be estimated and these will be used to evaluate the importance of roughness variations.

Vertical transfer of mass or momentum above a rough surface is determined by the appropriate turbulent exchange coefficient. The vertical exchange coefficient for momentum can be expressed, through Equation (3-1), as

$$K_M \equiv \frac{u_*^2}{\frac{\partial u}{\partial z}} = u_* k (z-d) \qquad (3\text{-}3)$$

It can be seen that d affects the exchange coefficient only through a displacement of the origin of height measurements. The effect of z_o is not explicit in Eq. (3-3); it enters through the friction velocity u_*.

The role of z_o in determining K_M can be made evident by expressing K_M in terms of height and the wind speed at a given reference level. Let us choose a reference height, measured from d, and denote this height as $(z-d)_a$. The wind at $(z-d)_a$ will be called $\overline{u}_a$. Then from Eq. (3-1)

$$u_* = \frac{k\overline{u}_a}{\ln \frac{(z-d)_a}{z_o}}$$

and therefore

$$K_M = \frac{k^2 \overline{u}_a (z-d)}{\ln \frac{(z-d)_a}{z_o}}$$

which explicitly shows the dependence of K_M on both z_o and d.

To illustrate quantitatively the effect on vertical exchange of an extreme difference in roughness between two sites, let us consider a short grass surface with z_o of 1 cm and a forest with roughness length z_o = 200 cm. The ratio of exchange coefficients for the two cases at equal distances

above the level d appropriate to each will be

$$\frac{K_M\,(z_o = 1)}{K_M\,(z_o = 200)} = \frac{\ln \frac{(z-d)_a}{200}}{\ln \frac{(z-d)_a}{1}} = \frac{\ln\,(z-d)_a - 5.3}{\ln\,(z-d)_a}$$

If the reference height is of the order of 20 m, or twice the tree height, the ratio of K's will be 0.3; i.e. the turbulent exchange coefficient over the rough surface is of the order of three times that over the smooth surface at equal heights (measured from d).

It is evident that the roughness length for a vegetation-covered surface has a significant influence on the turbulent exchange above the surface. Of course, if we compare different types of forest, rather than forest versus grass, z_o will probably vary by at most one order of magnitude and the change in K will be considerably smaller than in the above example. Changes in K_M between different surfaces can still be as large as a factor of two, however.

Rather than assuming that the above-canopy wind is the same for each case, it might be more logical to assume that the geostrophic wind, i.e., the horizontal pressure gradient, is the same for two surfaces of different roughness. To examine the roughness effect from this viewpoint, define the "surface Rossby number," R, by

$$R = V_g/F\,z_o$$

where V_g is the geostrophic wind and F is the coriolis parameter. Also, define a "geostrophic drag coefficient"

$$C = u_*/V_g$$

C is a function of R; empirical relationships between C and R are given in the literature, and are summarized by Johnson (51). Taking z_o values of 20 and 200 cm as likely forest extremes, R would change by one order of

magnitude. Johnson's curves indicate a change of about 20% in C for this range of R. Since

$$K_M = u_* k(z-d)$$

we have

$$K_M = C\ V_g k(z-d) \tag{3-4}$$

Thus, when we disregard the absolute wind speed and assume the same pressure gradients over two forests which differ markedly in roughness, we find a significant though not overwhelming difference in vertical exchange coefficient of 20% between the two forests. Using the same arguments based on surface Rossby number and known boundary layer relationships, it can readily be shown that the intensity of the vertical component of turbulence varies with surface roughness to about the same extent as does K_M.

B. Other Influences of Canopy Structure and Roughness

We have shown that turbulence and vertical exchange above a forest are dependent on the roughness of the canopy top. This dependence, though significant, is probably not strong enough to produce drastic differences in aerosol diffusion in the free atmosphere above forested land. Other effects, such as wind speed and thermal stability, are at least as important (see Appendix A). However, transfer through and below the canopy is much more sensitive to canopy properties. Let us first consider vertical exchange at the level of the canopy top.

The zero plane displacement must depend physically on the actual geometric roughness of the canopy and also on the density, number of openings, etc. As shown above, differences in d simply shift the origin of height and do not change the magnitude of turbulence at a given height above d. However, near the canopy top the shift of height scale can very strongly influence the turbulence intensity at just that height where it is important--at the height of the canopy. For an example, consider two of the forest types listed in

Table I, the bare deciduous forest and the larch stand. Both consist of trees approximately 10 m in height, and both have roughness lengths of about one meter. But d = 1 m for the deciduous forest versus d= 6 m for the larch. From Eq. (3-4),

$$K_M = C\ V_g\ k(z-d)$$

At z = 10 m, it is seen that K_M will be more than twice as large in the deciduous forest as in the larch, even for identical drag coefficients, which will in turn lead to much greater diffusion vertically through the canopy. Such a difference is, of course, expected in view of the openness of the bare deciduous forest as contrasted to the dense larch stand. The same sort of difference can be expected however for two stands of similar trees that differ in spacing, crown closure, or uniformity of density.

The treatment above considered mean velocity profiles, turbulent exchange and turbulence intensity, at and over a rough surface. This is about as far as it is possible to go on the basis of current theory and available data. Diffusion theory as it now exists relates only to flow over a uniform level surface. However the scale of turbulence and the turbulence spectrum over and within the forest, and the closure and homogeneity of the canopy should also be considered. Such factors apparently are highly important in governing diffusion. An example is offered by the Devil Hole test series (70). Changes in aerosol concentration within the forest were found to be closely related to vertical exchange through canopy openings and at discontinuities in tree height or type.

Holes or low places in the canopy, though they may be infrequent and randomly spaced, provide regions where aerosol can penetrate vertically in air flow induced by local pressure gradients or random gusts. The scale of variations in height of the tree crowns influences the scale of the turbulence above. One may in fact find that the turbulence intensity over a forest is comparable to that over an unforested site but that the scale of turbulence at canopy height is larger, thus leading to greater penetration of air flow

in favorable spots. Discontinuities in forest characteristics also lead to pressure gradients, local channeling of the flow and again increased ventilation in selected locations. Finally, inhomogeneities produce nonstationary boundary layer flow which is not in equilibrium with the lower bounding surface. Again, this increases the likelihood of flow through the canopy. The few spectra measured or estimated for below-canopy turbulence (for example Allen (2), Litton (92, 93), Melpar (60, 61)) do not give a clear picture of scales and frequencies below the canopy, but they do suggest that lower frequency, large scale variations are relatively more important in penetration and below-canopy transport.

To summarize, it has been shown that the aerodynamic roughness of the canopy top has a significant influence on turbulent exchange above the forest. These same roughness characteristics can have a profound effect on the mean vertical transfer rate at the canopy surface. And larger-scale variations, inhomogenieties, and discontinuities in forest structure are expected to produce very important local fluctuations of vertical transfer. Thus, the following analyses have sought to characterize the forest canopy in these terms. The proposed statistical analysis of canopy height (Chapter VI) is directed toward providing a quantitative measure of the canopy properties we have discussed. Such quantitative measures are believed to represent the bases of a classification or index system for the central problem of vertical transfer through the canopy.

IV. CONCLUSIONS BASED ON PREVIOUS FIELD TEST RESULTS

A number of diffusion and munition tests have been performed by DTC and others to obtain field data in forest environments. All available test results have been reviewed as part of the present study, and limited analyses of test data have been performed where appropriate to compare results from different environments. Available data cover a wide range of munition types, meteorological conditions, forest characteristics, terrain types, and observation methods. Because of the great number of variables in the tests and the varying forms of data analysis and presentation, the test data do not in general lend themselves to quantitative comparisons between forests. However, it has been possible to make comparisons for tests using fluorescent particles; the comparisons are discussed in this chapter.

The results of previous tests have provided quantitative data for specific combinations of terrain, forest, meteorology, and munition as intended in the test design. Most tests have also provided increased insight into some aspects of aerosol transport. However, it is believed that a specially designed series of tests will be required to provide definitive data for a forest classification system.

In accordance with the hypothesis that vertical transfer is the most significant parameter of forest effects, particular attention has been devoted to obtaining, from past test results, forest comparisons relating to either aerosol or momentum transfer through the canopy. Meaningful comparisons have been obtained for these cases, primarily because strictly meteorological measurements, which are available from all tests, can be used. This Chapter describes the relationships between vertical transfer, forest type, and atmospheric stability that have been defined, and which form the basis for the definition of an environmental index presented in Chapter V.

A. Wind Speed and Vertical Ventilation Rate

Solomon and Halvey (86), in ORG Note 29, have combined the results of field trials conducted in four different types of vegetation with Calder's (16) canopy penetration model to compute canopy ventilation rates. Ventilation rate is defined, in terms of the Calder model, as the number of changes of air per unit time. The trials involved were the Bendix trials (42, 43, 94) in a tropical rain forest, the Big Jack trials (81, 82) in a jungle and the Litton trials (92, 93) in a deciduous forest during both summer and winter seasons. The data used in the Note were mean above- and below-canopy wind speeds, above-canopy stability*, above-and below-canopy fluorescent particle (FP) dosages, height of releases and downwind distance from release point. Below-canopy measurements were characteristically made a few meters above the ground and above-canopy measurements made 10 to 15 m above mean canopy height.

ORG Note 29 showed, from the collected field data and computed ventilation rates, that ventilation rate increases with increasing wind above the canopy and decreases with increasing above-canopy stability, both for any given forest. Moreover, the ORG 29 results indicated that for a given above-canopy wind, ventilation rate appears to increase with decreasing density of the forest. These results are, of course, in accord with what might be expected on physical grounds.**

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* It was learned through private correspondence with Mr. Irving Solomon that the above-canopy stability categories for the tropical rain forest are in error in ORG Note 29. Mr. Solomon provided above-canopy temperature data--not included in the referenced Bendix report--which indicate that stable and neutral stability categories in the Note should be interchanged. The revised stabilities are used in this report.

** As a point of interest, the meteorological and dosage data, as well as computed ventilation rates, suggest that the jungle and summer deciduous forest are so similar that they could be considered to be essentially the same forest category. However, the site chosen for the jungle trials was in a valley. The prevailing air flow was such that there was a net downward motion through the canopy. This superimposed orographic influence may have acted to give the jungle the diffusion characteristics of a forest with a less dense canopy.

For purposes of applying the Calder model to field data, Solomon and Halvey computed mean ratios of below-to-above-canopy wind speed ($\overline{u}_b/\overline{u}_a$) for each type of forest. These ratios indicate that $\overline{u}_b/\overline{u}_a$ increases with decreasing forest density. Since $\overline{u}_b/\overline{u}_a$ varies with general forest density in the same direction as does ventilation rate, and since both parameters would be expected, from physical reasoning, to depend directly on turbulent exchange through the canopy, it follows that $\overline{u}_b/\overline{u}_a$ might serve as a useful index to any forest's effect on vertical transfer of diffusing material. In particular, the ORG results suggest that for given meteorological conditions (stability and wind above the forest) $\overline{u}_b/\overline{u}_a$ and ventilation should both depend directly on the forest type.

To provide a test of this hypothesis, the test data of ORG 29 were reorganized and displayed as a plot of ventilation rate versus $\overline{u}_b/\overline{u}_a$. The result is shown in Figure 1. The figure contains plots of the mean ventilation rate for a given test (regardless of release height or downwind distance from release point) and the ratio of mean below-canopy wind speed ($\overline{u}_b$) to mean above-canopy speed ($\overline{u}_a$) for the same test. Different symbols were used to denote forest types and above-canopy stability conditions. The general trend of the data indicates that as forest type varies, ventilation rate and wind speed ratio are related in a linear manner; the dashed lines represent ±50 per cent variation in ventilation rate about the best-fit straight line. Note that the data should <u>not</u> be interpreted as implying that ventilation rate varies linearly with wind ratio <u>within a given forest category</u>. The scatter of points for each single forest type must be due largely to variations in meteorological conditions under which tests were run. But the trend of mean values of ventilation and $\overline{u}_b/\overline{u}_a$ for different forests supports the hypothesis that for given stability and above-canopy wind, ventilation rate is approximately a linear function of wind ratio; i.e., ventilation rate and wind ratio are both uniquely related to forest type. Thus, if the wind ratio in a given forest were known for some standard meteorological conditions, the ventilation rate could be predicted without further knowledge of the forest characteristics. This capability for predicting ventilation from the wind ratio is particularly useful since wind data exist for many forest types where diffusion experiments have not been carried out,

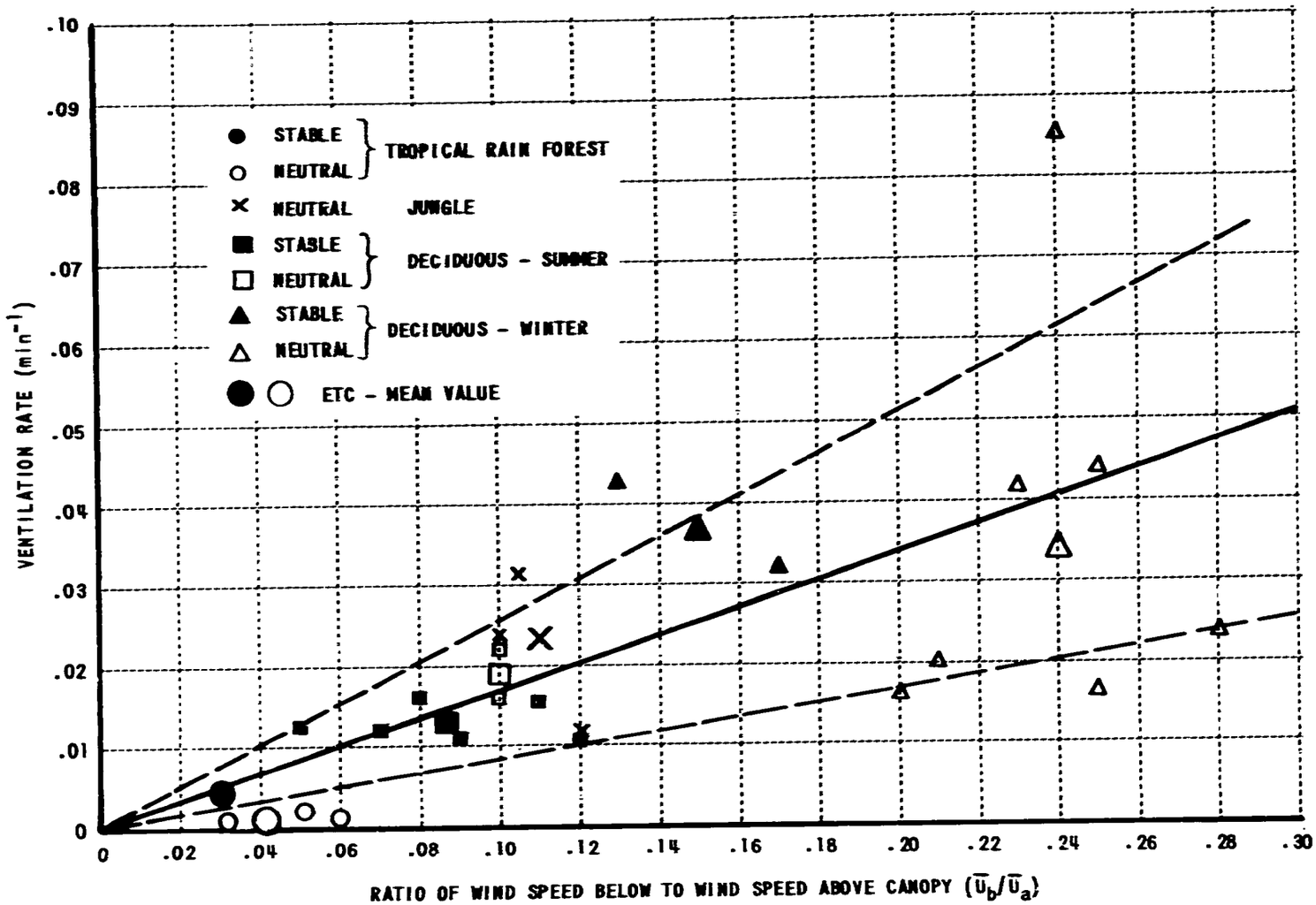


Figure 1 RELATIONSHIP OF VENTILATION RATE TO WIND SPEED RATIO

and are much more readily obtained than diffusion data where additional field data are needed. Further, it confirms that a forest index based on wind ratio will provide a meaningful measure of the forest's retardation to vertical diffusion through the canopy.

B. Dependence of Wind Ratio on Forest Type

To further verify that the ratio of wind speeds above and below canopy provides a measure of vertical transfer through the canopy, and therefore an index of forest character, wind data from a number of field tests have been analyzed. The specific objectives were to determine whether a consistent difference between forests could be identified from wind and stability data alone, and to define quantitatively the relationship between $\overline{u}_b/\overline{u}_a$ and the primary meteorological variables of stability and wind speed above the canopy for various forests.

Meteorological measurements* from the four trials tabulated in ORG Note 29 (86) and the Melpar trials in a South Carolina "rain forest" (60, 61) have been plotted (Figures 2 and 3) for neutral and stable above-canopy conditions, respectively. Since different definitions of $\overline{u}_b/\overline{u}_a$ were used for the various trials, the heights of the measurements are listed in Table II.

*All of the trials discussed here suffered from the inability to measure the low wind speeds that are known to exist within a forest. On the whole, wind speeds less than 0.2 to 0.3 m sec^{-1} were below the sensitivity threshold of the instruments.

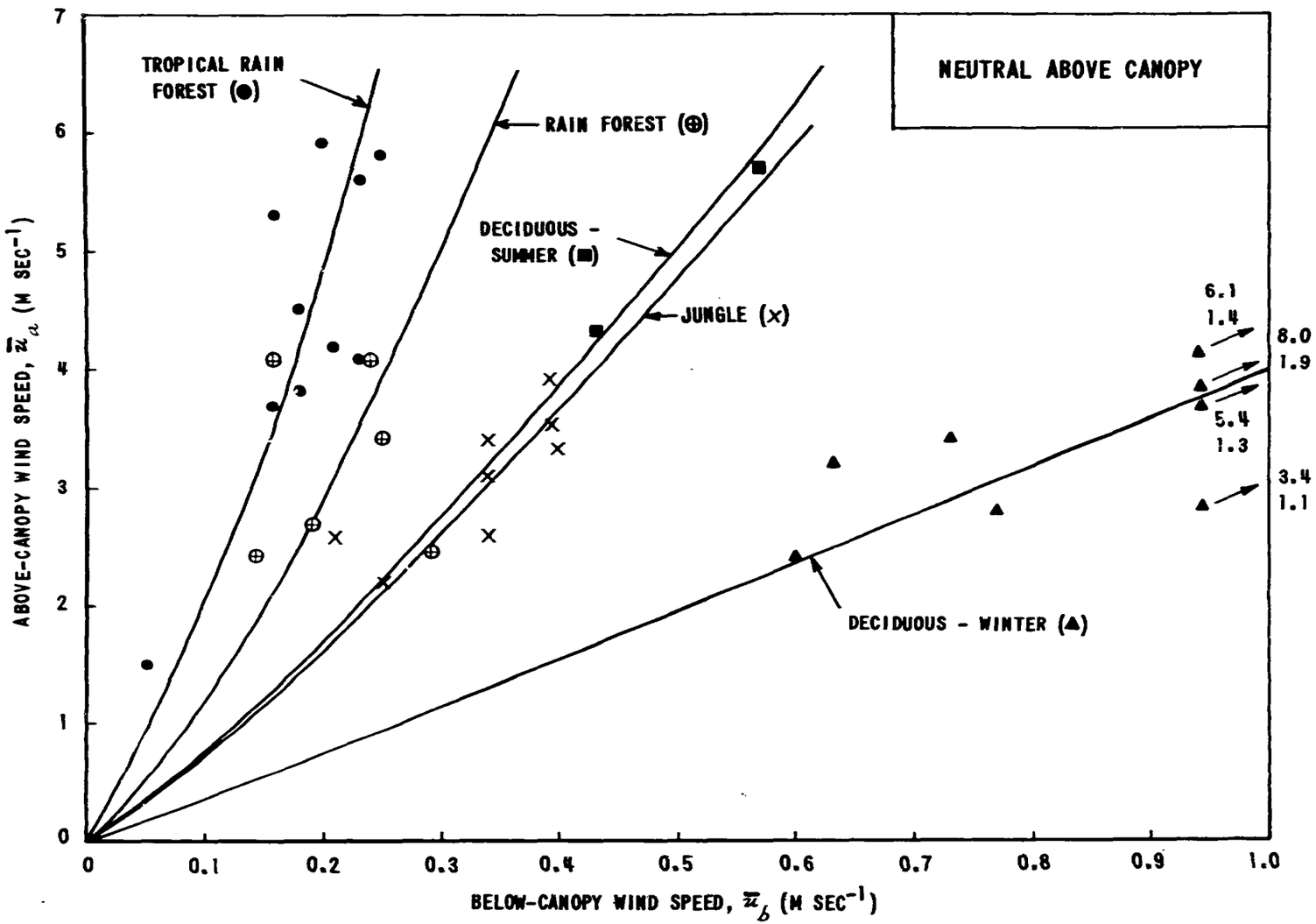


Figure 2 ABOVE- AND BELOW-CANOPY WIND SPEEDS FOR VARIOUS FORESTS UNDER NEUTRAL ABOVE-CANOPY STABILITY CONDITIONS

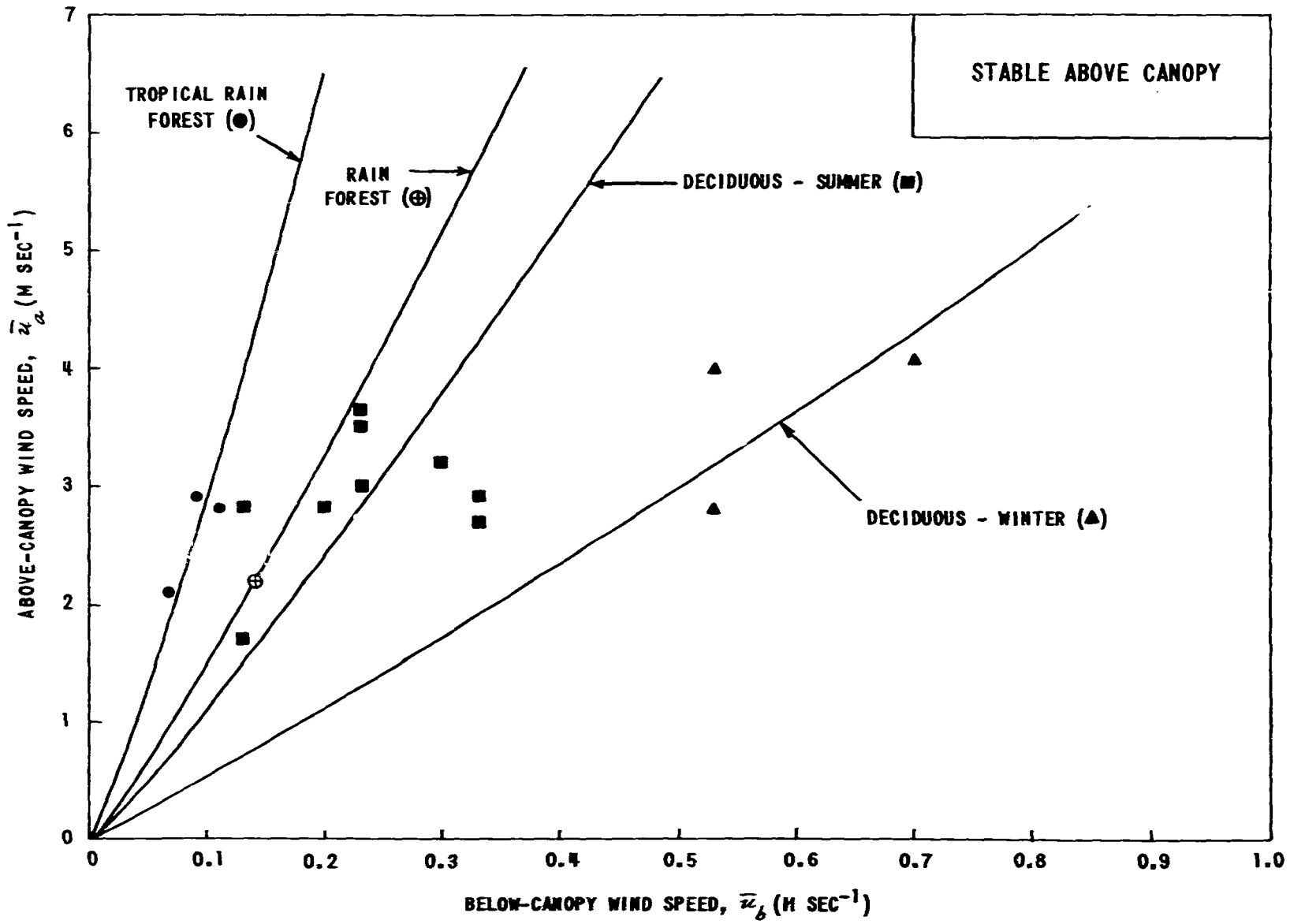


Figure 3 ABOVE- AND BELOW-CANOPY WIND SPEEDS FOR VARIOUS FORESTS UNDER STABLE ABOVE-CANOPY CONDITIONS

Table II

Height of Wind Speed Measurements Above Ground and Above Canopy

Forest Type	$\bar{u}_b$ Height above ground (m)	$\bar{u}_a$ Height above canopy (m)
Tropical Rain Forest (Bendix)	Average (2 and 9)	15
Rain Forest (Melpar)	Smoke puffs 1, 5	13
Tropical Jungle (Big Jack)	Average (2 and 12)	12
Deciduous - Summer (Litton)	Average (1, 5 and 10)	10
Deciduous - Winter (Litton)	Average (1, 5 and 10)	10

Figure 2 indicates three groups of forests: 1) tropical rain forest (Bendix) and rain forest (Melpar), 2) tropical jungle (Big Jack) and deciduous summer (Litton) and 3) deciduous winter (Litton). The forests follow the expected trend where a steeper sloping line (that is, a denser forest) indicates a lower below-canopy wind speed. Also, each forest has a consistently steeper line for positive (Figure 3) as compared to neutral above-canopy stability. The slight curvature of the lines reflects the fact that wind ratio is not constant for a given forest and stability, but decreases slightly with increasing $\bar{u}_a$.

C. Relationship Between Dosage Ratio and Wind Ratio

In ORG Note 29, Solomon and Halvey (86) organized above- and below-canopy FP dosage data in connection with their evaluation of Calder's (16) canopy penetration model. In the present work, attempts to relate ratio of below- to above-canopy dosage (D_b/D_a) to downwind distance (1 to 7 km) and height of release proved to be fruitless. However, attempts to relate the dosage ratios (regardless of release height or downwind distance of sampler) to wind speed ratios proved to be successful. Figure 4 shows the means and extremes of dosage ratios and wind speed ratios for various forest and stability conditions. In spite of the appreciable spread of the

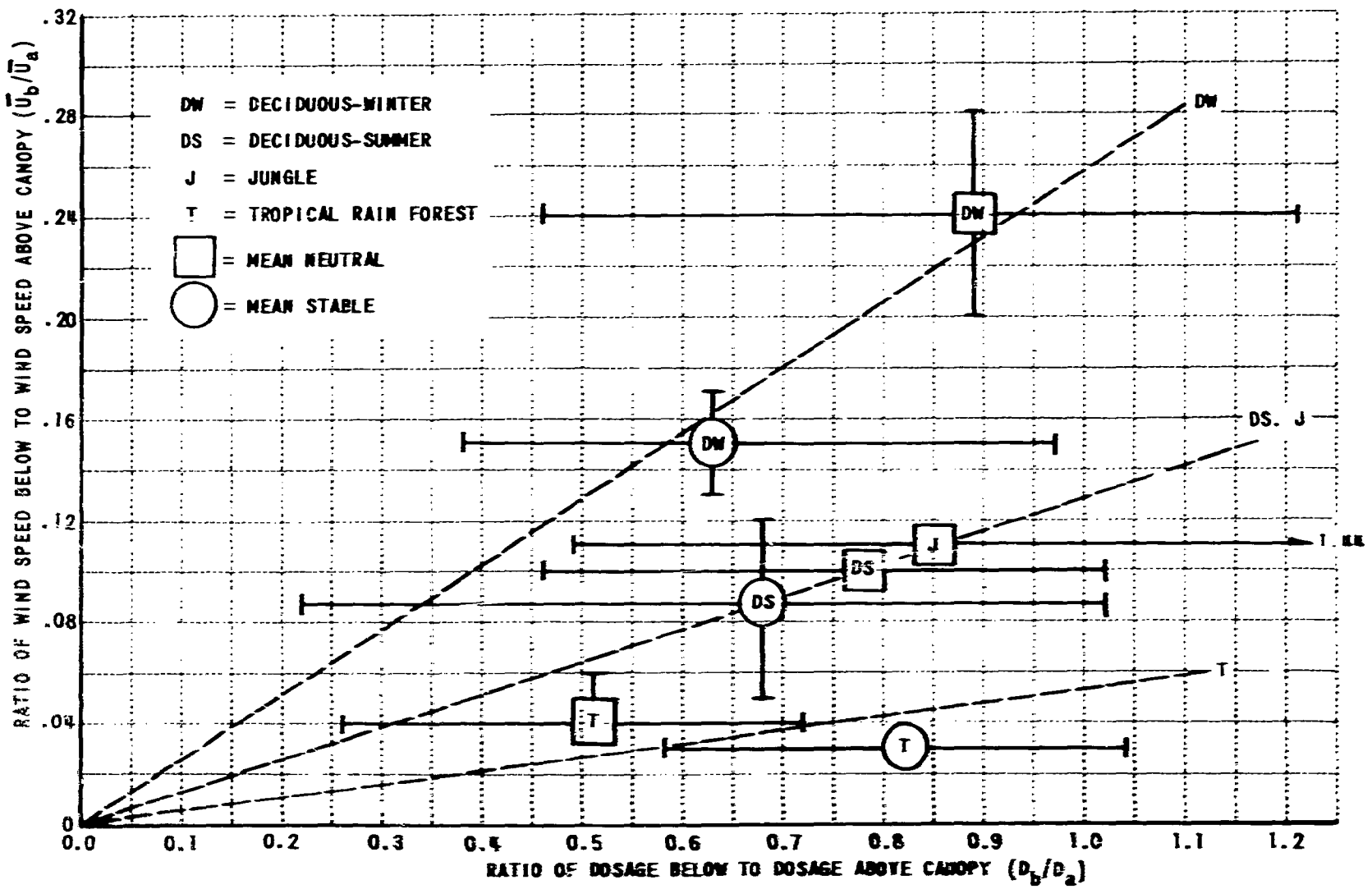


Figure 4 INFLUENCE OF FOREST TYPE AND WIND SPEED RATIO ON DOSAGE RATIO

individual data points (indicated by the capped horizontal and vertical lines), the means for a given forest seem to suggest that there is a linear relationship between the wind ratios and the dosage ratios. Since theoretically the dosage ratio depends on distance and ventilation rate, one would expect some correlation between wind and dosage ratios on the basis of the result shown in Figure 1. The great scatter is undoubtedly due to variations in downwind distance as well as meteorological conditions. However, the consistency in the slope variation with forest type again demonstrates the usefulness of wind ratio for characterizing the forest influence.

D. Comments on Diffusion Tests

Figures 1 through 4, which are based upon a limited variety of measurements, suggest the type of quantitative results that should be obtained from measurements made in a large number of meteorological and forest situations. One serious problem which probably contributes to the scatter in all of the figures is the lack of sensitivity in measuring wind speed within a forest. All trials discussed above used wind measuring instruments which were inadequate for making wind measurements at the low velocities common within a forest. It is regretable that instrumentation has not advanced to the point where low wind speeds can readily be measured in the field.

In this Chapter, attention has been devoted only to the problem of downward penetration of aerosols through a forest canopy. Available results suggest that with more data, conclusions similar to those presented above could be obtained for below-canopy releases. For example, both the Litton (29, 93) and Melpar (60, 61) tests indicate that aerosol clouds released near the ground travel in a direction which is counterclockwise of the wind direction above the canopy. The counterclockwise departure is greater for the more stable above-canopy conditions and for the denser forests. With measurements made in a variety of forests under a variety of meteorological conditions, a nomogram relating below- to above-canopy wind direction could be constructed. As another example, the spread and degree of meandering of ground-released aerosol clouds could be related to above-canopy meteorological conditions in a manner suggested by Figure A-5 in Appendix A.

V. A PROPOSED ENVIRONMENTAL INDEX

Canopy roughness and permeability, together with above-canopy winds and stability, appear to be the primary factors governing vertical diffusion above and within a forest. Up to the present time no canopy roughness measurements have been made at test sites and only a few quantitative measurements of forest parameters have been made in an attempt to deduce canopy permeability. However, the measurement of aerosol dosages and meteorological parameters both above and below the canopy for most field tests have made it possible to relate the turbulent diffusion of aerosols to the associated meteorological variables. The results obtained in the previous Chapter suggest that an environmental index might very soundly be based upon meteorological measurements which--due to their very nature--reflect the physical characteristics of the forest in which they are made. On the basis of the relationships shown in Chapter IV, we have attempted to use meteorological parameters to establish an environmental index for the forests in which diffusion tests have been run.

The proposed index is defined in terms of the relationships shown in Figures 2 and 3. Since the slope of the curves, for a given stability, is a function of forest type (presumably including the effects of density, roughness, and closure), one can, in some manner, relate an environmental index to the slope of the curve. It seems desirable to select neutral conditions as the reference above-canopy stability category (neutral stability corresponds to a Richardson number (R_i) of zero). Considering then, Figure 2, it is noted that the curvature of the lines prevents the determination of a unique slope for each forest. Therefore, it is proposed that the Environmental Index (E.I.) be defined by the ratio $\overline{u}_a/\overline{u}_b$, evaluated at an arbitrarily-chosen above-canopy wind speed of 5 m sec^{-1}:

$$E.I. = \left(\frac{\bar{u}_a}{\bar{u}_b}\right)_{R_{ia} = 0,\ \bar{u}_a = 5\ m\ sec^{-1}} \tag{5-1}$$

where R_{ia} is the above-canopy Richardson number defined as

$$R_{ia} = \frac{g}{\theta}\left(\frac{\partial T_a}{\partial z} + \Gamma\right) \Big/ \left(\frac{\partial \bar{u}_a}{\partial z}\right)^2 \tag{5-2}$$

where g is acceleration due to gravity, θ is potential temperature, Γ is dry adiabatic lapse rate and where $\partial/\partial z$ is vertical gradient for above-canopy temperature (T_a) and wind speed ($\bar{u}_a$).

Table III lists Environmental Indices for the forest types in Figure 2. However, since the data in the figure represent a variety of near-neutral conditions, the Indices are only approximate. A suitable procedure for determining E.I. for a given forest would be to make measurements of $\bar{u}_a$ and $\bar{u}_b$ under a variety of above-canopy stability and wind speed conditions. By plotting R_{ia} as a function of $\bar{u}_a$ and $\bar{u}_b$, a family of best-fit curves can be drawn and the $R_{ia} = 0$ curve will thus be determined as accurately as possible. An example of this procedure is shown in Figure 5, using a limited number of measurements from a deciduous forest in winter. The above-canopy Richardson numbers, tabulated in the Litton report (92, 93), were computed for the depth from 7 m below the top of the canopy to 23 m above the canopy. The curves--as drawn--indicate that the Environmental Index should be 3.6, as compared to the value of 4.0 obtained from less precise stability data in Figure 2.

Table III

Environmental Indices for some forests in which diffusion tests have been made

Forest Type	Environmental Index
Deciduous-Winter (Litton)	4.0
Jungle (Big Jack)	9.5
Deciduous-Summer (Litton)	10
Rain Forest (Melpar)	17
Tropical Rain Forest (Bendix)	24

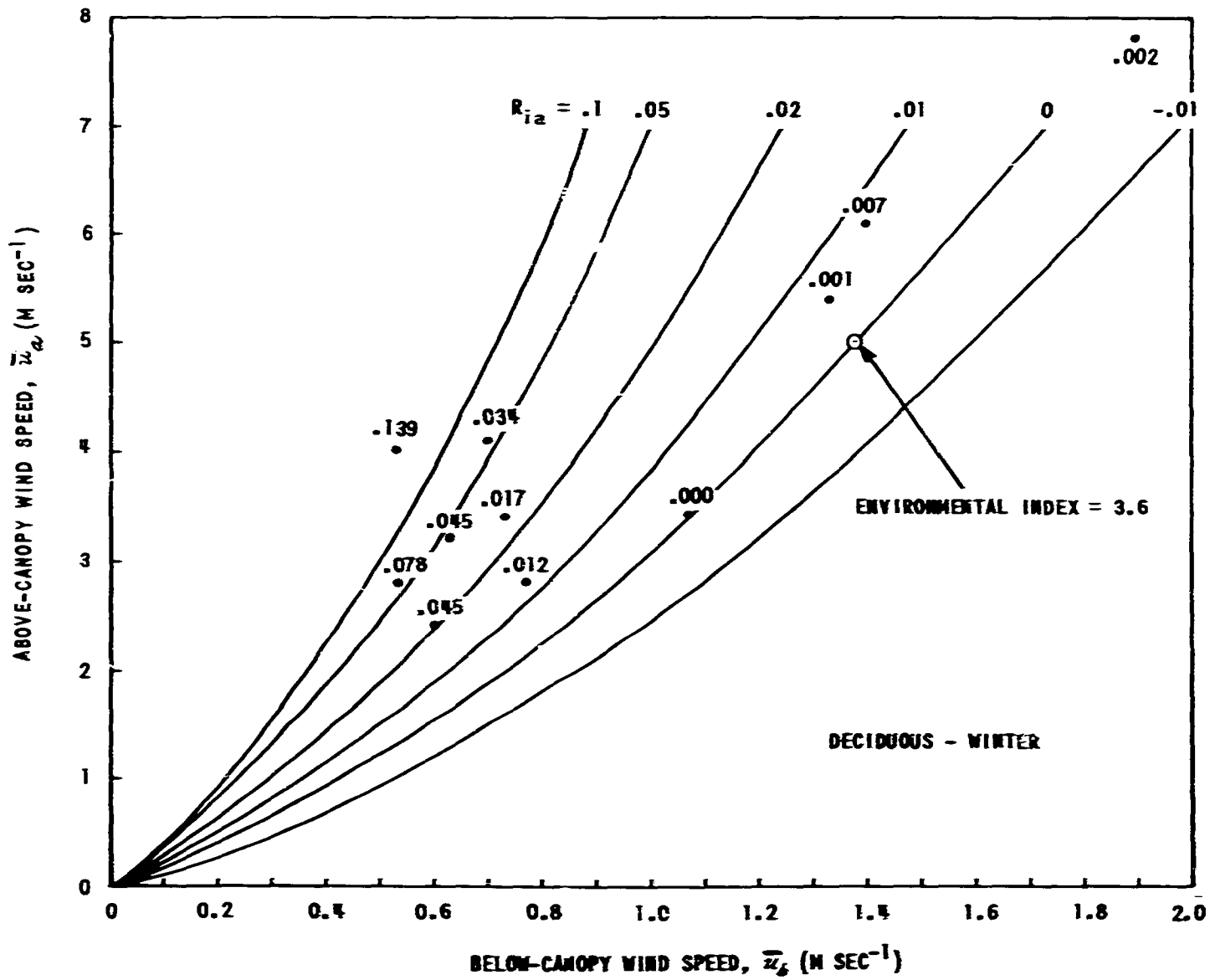


Figure 5 EXAMPLE OF PROCEDURE FOR DETERMINING ENVIRONMENTAL INDEX FOR A DECIDUOUS FOREST IN WINTER

In order to have consistency in heights at which measurements are made in future tests, the following arbitrary heights are recommended:

$\bar{u}_b$ - 1.5 m above ground

$\bar{u}_a$ - 10 m above canopy

R_{ia} - over height interval from top of canopy to 10 m above canopy

The lack of height consistency, as indicated in Table II, may have introduced errors in the relative positioning of the various curves in Figures 2 and 3. Positioning errors in the curves for the more dense forests were also due to lack of sensitivity in measuring below-canopy wind speed.

The relationships between wind ratio and dosage ratio depicted in Figure 4 can be used to give a first estimate of below-canopy dosage in terms of the Environmental Index for a forest. In Figure 6, the inverse slopes of the lines in Figure 4 are plotted as a function of the Environmental Indices. The capped vertical lines represent the range of dosage ratios in the previous figure. The dashed lines indicate inverse slopes 50 per cent larger and smaller than the mean lines in Figure 4. The linear relationship in Figure 6 permits one to derive a general expression for the dosage level within a forest resulting from an above-canopy release. The equation for the solid line is

$$\frac{D_b/D_a}{\bar{u}_b/\bar{u}_a} \Big/ E.I. = 0.8$$

Since the dashed ±50 per cent lines represent the general spread of the values, the below-canopy dosage can be expressed as

$$D_b = (0.8 \pm 0.4)\,(E.I.)\,\frac{\bar{u}_b}{\bar{u}_a}\,D_a \qquad (5\text{-}3)$$

Equation 5-3 provides an expression for D_b which is based on the Environmental Index for a given forest and the wind speed ratio at the time of a trial having an above-canopy dosage of D_a. The variation of the coefficient between 0.4 and 1.2 reflects the trial-to-trial variation due to differences from

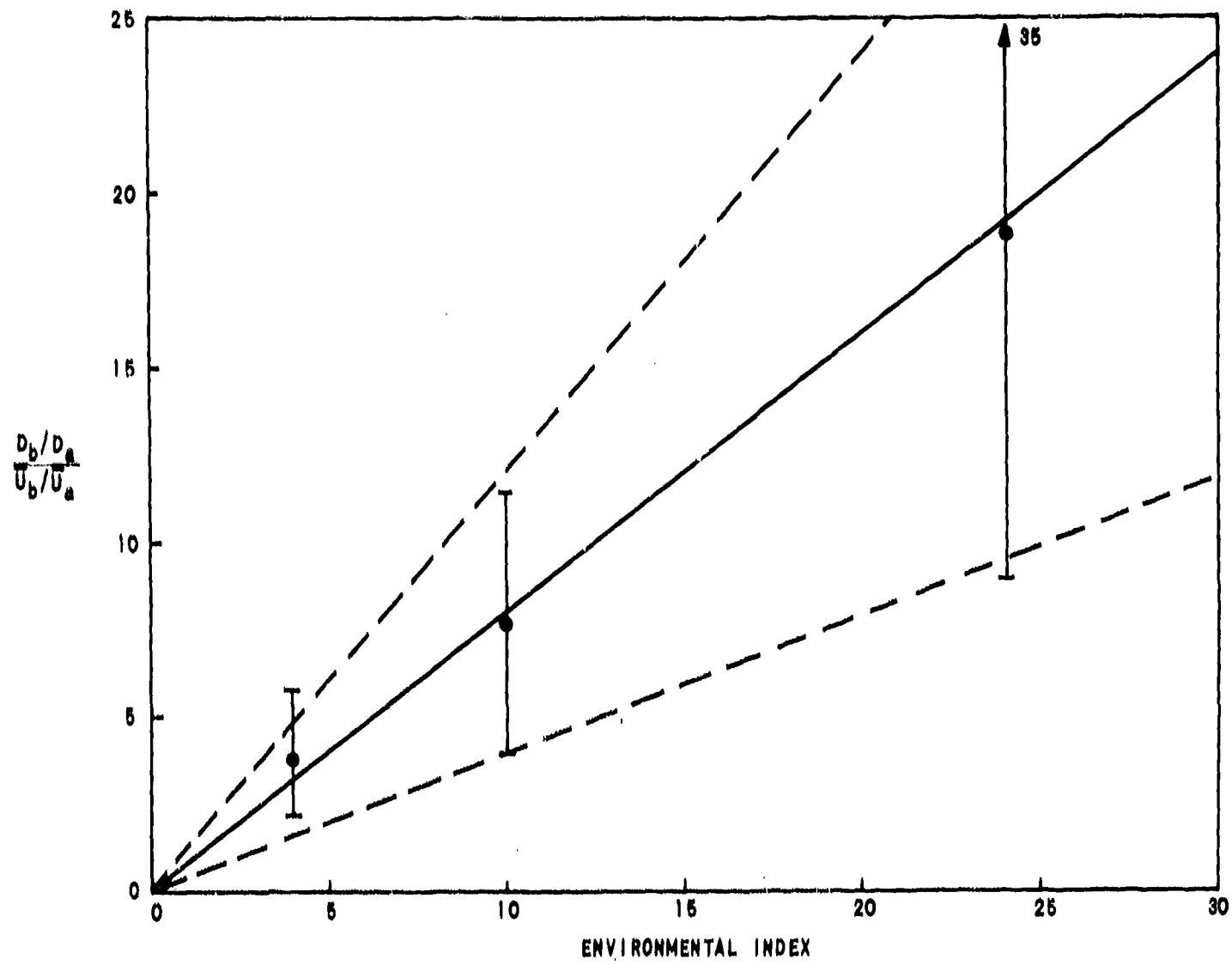


Figure 6 DEPENDENCE OF DOSAGE AND WIND SPEED RATIOS ON ENVIRONMENTAL INDEX

standard meteorological conditions and various downwind distances. With additional data, refinements to Eq. 5-3 could be derived to account for distance, stability and above-canopy wind speed effects. However, the equation as stated shows the mean influence of forest characteristics on dosage ratio.

The proposed Environmental Index promises to be highly useful in describing canopy penetration and diffusion within a forest. However, there is no way at present to relate the Index to a quantitative forest description which would allow one to assign an E.I. to a given forest without prior meteorological measurements. As discussed earlier, canopy penetration for a given type of forest must be a function of canopy roughness, closure, and density. Thus, the Indices computed in this Chapter for various forests reflect, in an integrated way, the structure of each forest in terms of the roughness, closure and density of its canopy.* In the following Chapter several methods for determining the roughness and closure from aerial stereo-photographs are outlined, and a procedure is proposed whereby the Environmental Index could ultimately be related directly to canopy measurements.

*In the case of the Big Jack jungle trials (81, 82), there also appears to be the added influence of topography.

VI. DEVELOPMENT OF A FOREST CLASSIFICATION SYSTEM

A. Approach

In the preceding pages it has been argued that characterization of the vertical transfer of mass and momentum through a forest will permit a general classification of all forests that can account for the principal variations in aerosol behavior. It has been demonstrated that measurement of momentum transfer (as indicated by the wind ratio) allows discrimination between physically different forest types and permits prediction of dosage ratios within the accuracy attainable with state-of-the-art models. A demonstration of the applicability of this approach to other diffusion characteristics such as growth of below-canopy clouds is not possible with existing data. However, physical reasoning and the qualitative results available from past experiments both suggest the validity of the concept. Further development of the approach, leading to final specification of a forest analog classification method, requires two fundamental steps:

1. Development of methods for relating readily observable (or previously measured) physical forest characteristics to the proposed Environmental Index.

2. A field test program encompassing a wide range of forest types to test the proposed concepts and to determine quantitative relationships between the forest parameters, index, and diffusion properties.

For step no. 1, two basic types of forest measurement will provide data that are very closely related to the meteorological and diffusion properties of importance. These are: a) measurement of light extinction at the ground (Appendix B) or total mass density of the forest (60, 61) and b) measurements of height of the forest top derived from aerial photographs. The present Chapter outlines several candidate approaches for

deriving the necessary data from aerial photographs and presents tests of the practicality of the methods.

The final Chapter of this report presents recommendations for the field test program required for step no. 2.

B. Methods for Measuring Canopy Roughness

The vertical transport of an aerosol through a canopy is dependent on the configuration that the surface of the canopy presents to air moving above it. The most general description of a canopy would be to have a functional relation between location and canopy height. Then the air flow over the canopy could be determined, at least in principle, from fluid flow theory. Actually applying this process, including developing a function for canopy height, is impractically difficult. A more useful, but much less general description can be realized by developing some sort of statistic or index which assigns a single number to a region of forest. This number is then thought of as a measure of roughness, and one tries to relate canopy roughness to diffusion characteristics. This approach has the disadvantage that combining the many properties of something as complicated as a forest canopy into a single index necessarily generalizes and may produce a loss of some of the information of interest.

Consideration of the above situations prompted a study of the problem of canopy roughness on several levels intermediate between the extremes mentioned above. Several methods have been examined to see whether they 1) characterize the roughness, and 2) discriminate canopies of different roughness. In some cases, discussed in Appendix C, the methods have been studied and tested on data other than those taken from forest canopies (geometrical shapes, sine waves, etc.). The results of these tests show the feasibility of using a particular method as well as giving an indication of the amount of calculation required for application. In addition, calculations were made on part of some forest canopy data taken from the aerial photography of the AMPIRT study area of Thailand (17). The methods discussed below are presented in more detail in Appendix C.

Digitization of Thailand Canopy

In order to test some proposed methods for measuring canopy roughness, aerial photographs were obtained for a 250 by 1400 m portion of a Thailand forest. Height measurements (or more precisely, parallax measurements from a given pair of photographs, since it was not possible to measure the height of the ground) were digitized at 2-m intervals in two different ways: 1) along a 200-m straight line randomly oriented over the canopy and 2) over 30 randomly placed 20 by 20 m windows. Figure 7b illustrates the type of placement used for the windows (only 15 are shown). The upper part of the figure indicates how each window was divided into 10 sampling windows; use of the sampling windows is discussed below.

Variance of Canopy Height

Before delving into the more complicated methods for measuring canopy roughness, one simple and straight-forward approach is to compute the variance of the height of the upper surface of the canopy. The variance reflects the amplitude--but not the frequency--structure of the canopy. As an illustrative example, the variance of the 200-m long profile in the Thailand forest was 21 m^2. This means that the standard deviation of canopy height along that one line was 4.5 m--a quantity which partially describes the roughness.

Variance Decay and Correlation Curve Methods

Two of the methods explored during this project to describe canopy roughness were based on 1) the decrease in variance of mean canopy height over a number of sampling windows as the size of the sampling window increases, and 2) the decrease in the correlation between the average height in a given sized sampling window and the last point in the window (lower right corner for square, rightmost end for profile) as the size of the sampling window increases. Using these methods, canopy roughness is thought to be related to parameters--such as the coefficients in a least-squares fit or various intercept values--of the curve for a given forest. One would expect, for example, a conifer forest curve to approach zero at a much faster rate than a curve for the

more slowly undulating canopy of a deciduous forest in leaf. Measurements of a number of forest canopies would be required in order to relate parameters of the curves with canopy roughness.

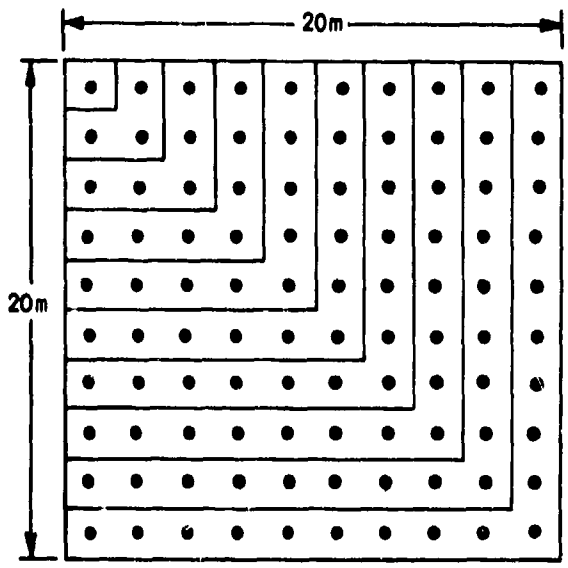
For measurements of the Thailand forest canopy, 10 square sampling windows ranging from 2 to 20 m on a side were used (see Figure 7a) for each of the 30 randomly-placed positions and a one-dimensional sampling window ranging from 2 to 140 m in length was used for the profile. The resulting variance-decay and correlation curves are shown in Figures 8 and 9, respectively. As mentioned above, it is not possible at the present time to properly interpret these curves without first making similar measurements in a variety of forests.

It was found that the square sampling window had several disadvantages compared to the one-dimensional window used for the linear profile. First of all, Figures 3 and 9 indicate that the largest sampling window should have been of the order of 100 m on a side instead of 20 m. However, it is preventive in both time and money to digitize height data at 2-m intervals over a sufficient number (at least 30) of 100 m squares. Secondly, since the ground was not visible in the aerial photographs, there was no fixed reference height from which the canopy height measurements could be made. Therefore each of the 30 square windows did not have a consistent reference height, which may have been responsible for the scatter of the data points in the two figures. Even though the profile also had an arbitrary reference height, the same reference was used for all digitizations and therefore the profile data points exhibited negligible scatter.

Crossing Statistics

The above discussion indicates that digitization along a line has greater feasibility than digitization over an area. This conclusion makes it possible to use an analysis method which is simpler in both principle and application than the variance-decay and correlation methods.

The simpler method is based on properties derived from the number of times that the top surface of the canopy crosses a horizontal line at a given



TEN WINDOW VALUES ($\bar{X}_{2i}$, $\bar{X}_{4i}$, $\bar{X}_{6i}$, $\bar{X}_{8i}$, $\bar{X}_{10i}$, $\bar{X}_{12i}$, $\bar{X}_{14i}$, $\bar{X}_{16i}$, $\bar{X}_{18i}$, $\bar{X}_{20i}$) CAN BE OBTAINED FROM EACH INDIVIDUAL 20 - m - SQUARE WINDOW

Figure 7a AN INDIVIDUAL WINDOW

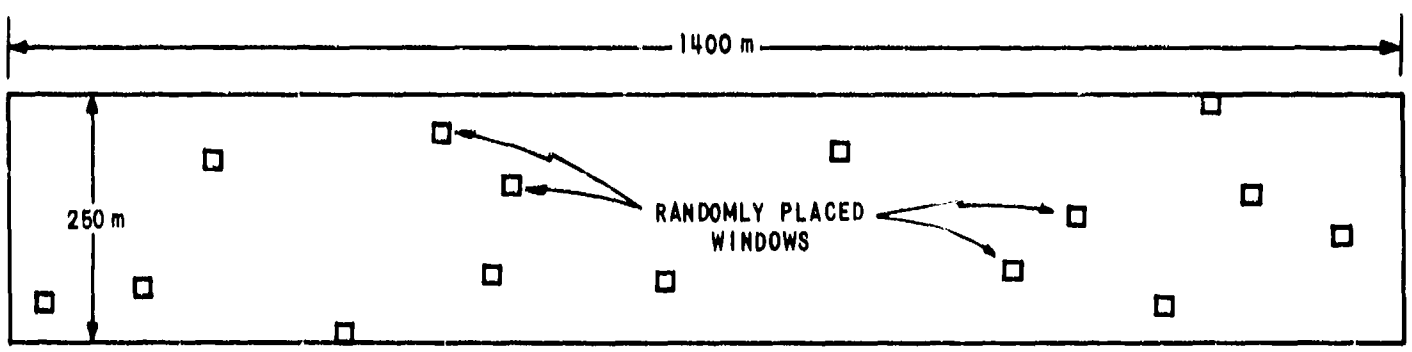


Figure 7b ENTIRE SAMPLING AREA

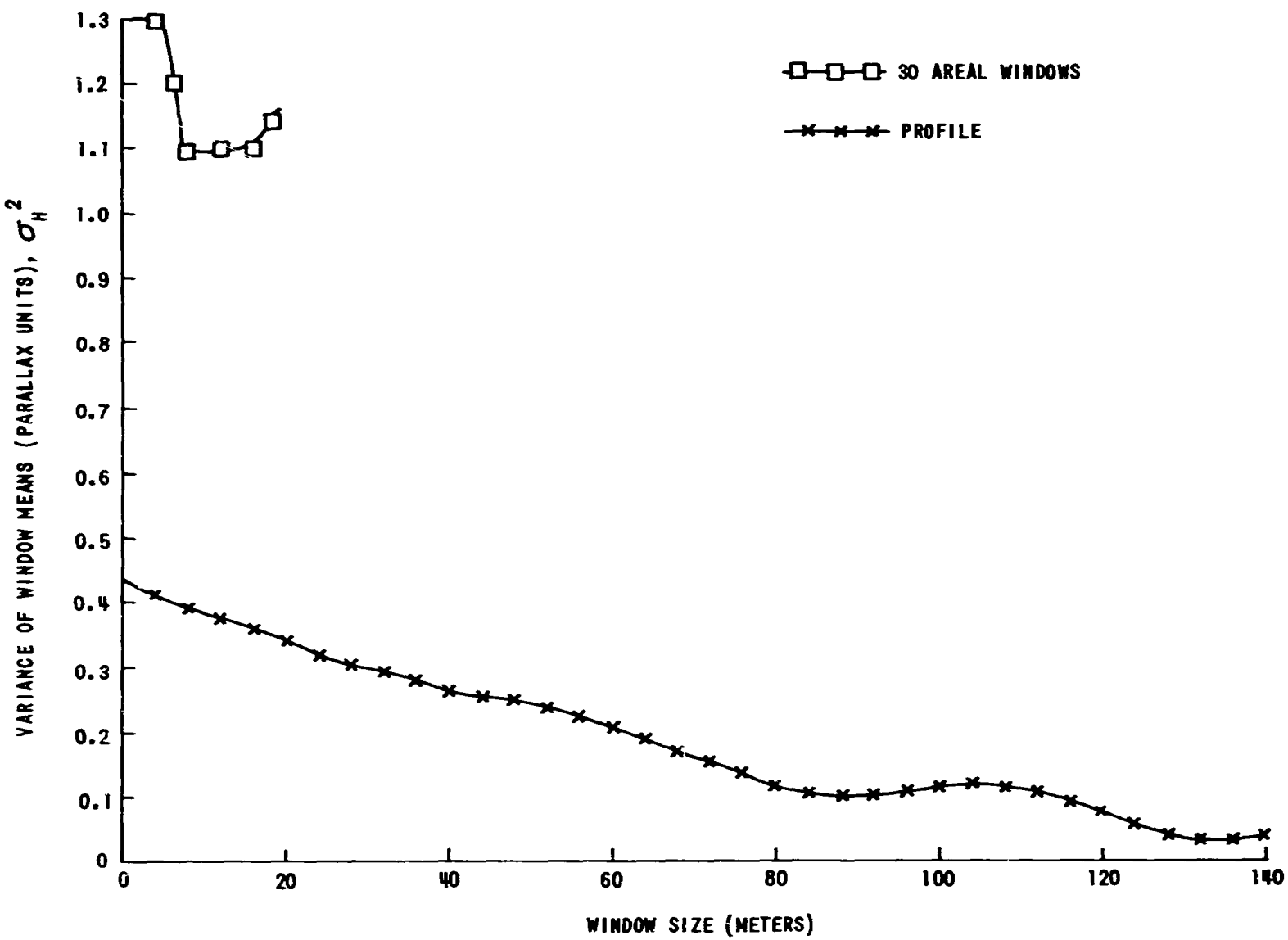


Figure 8 VARIANCE OF MEAN HEIGHT AS A FUNCTION OF WINDOW SIZE FOR A THAILAND FOREST CANOPY

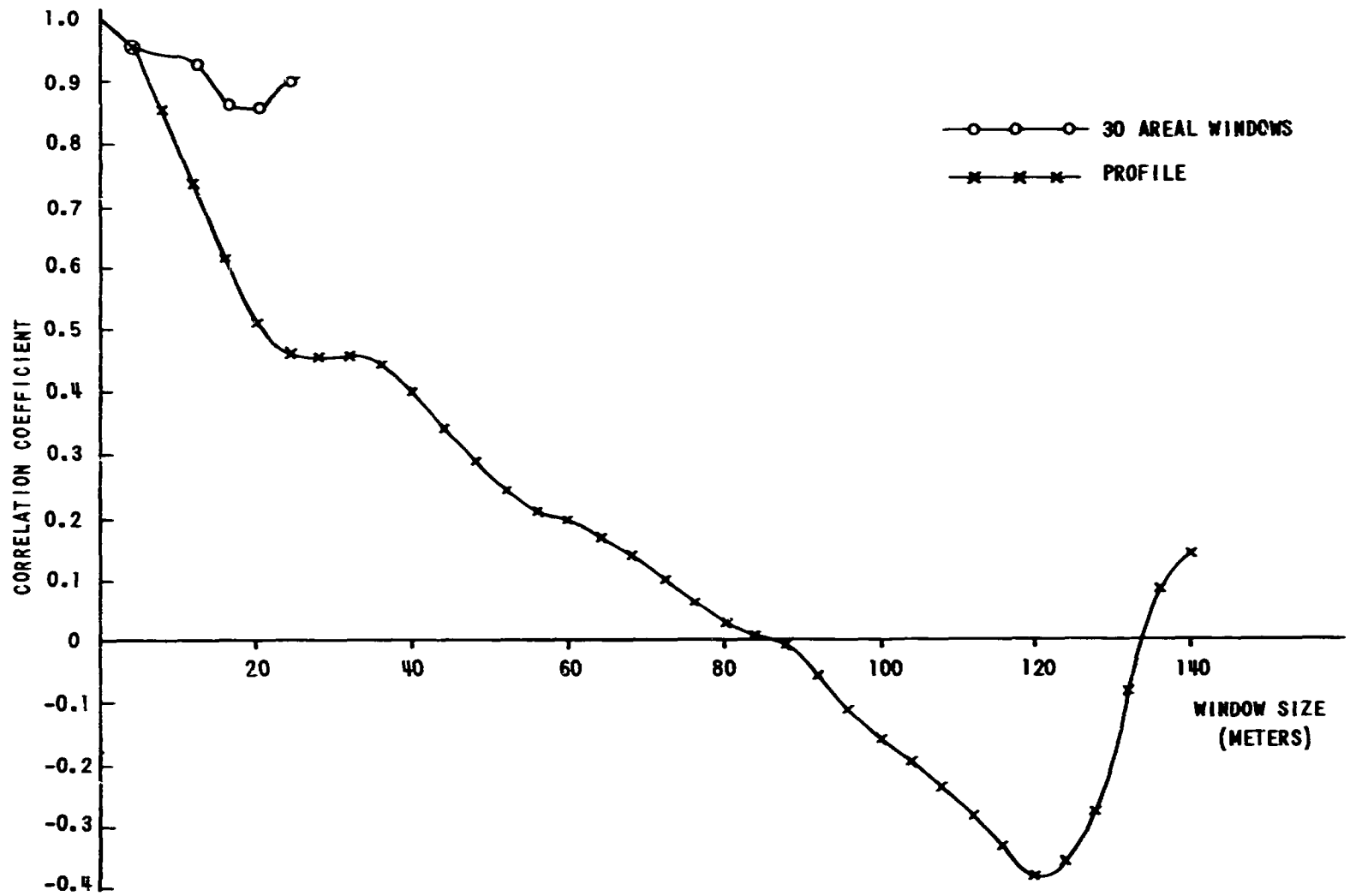


Figure 9 CORRELATION AS A FUNCTION OF WINDOW SIZE FOR A THAILAND FOREST CANOPY

height. The method makes use of the following two curves:

<u>β curve</u>, where $\beta(h)$ is the fraction of the length of a straight horizontal line at height h which is below the canopy profile.

<u>μ curve</u>, where $\mu(h)$ is the number of crossings per unit length that a straight horizontal line at height h makes with the profile.

Figure 10 shows the $\beta(h)$ and $\mu(h)$ curves computed for the 200-m long profile. The β curve contains information about closure as well as the geometric shape of the profile. For example, given a conifer forest with the same height as the Thailand forest, one would expect the β curve for the conifer forest to start decreasing at a lower height than does the β curve in the figure. The μ curve contains frequency information. The multiple peaks in the figure reflect a multiple-storied canopy.

The β and μ curves in Figure 10 can best be interpreted after they have been compared with β and μ curves for other forests. Unfortunately, measurements from other forests do not yet exist. As a substitute for the additional information, Richards plots (76) of three types of Thailand forests (64) were used to obtain quasi-profiles of the three canopies; a Richards plot consists of a schematic top and side view of all trees within a transect about 10 m wide and 40 to 200 m long. Judicious digitization allows one to obtain appropriate height measurements.

Figure 11 gives the β and μ curves for the three forests. It is clear that each forest has a distinctive curve. Note that the dry evergreen (190) and mangrove (270) both have the same maximum height element of 26 m. This makes it possible to directly compare those two forests. The β curve for the dry evergreen (not coniferous) decreases at lower heights than does the curve for the mangrove forest.

The μ curves for the dry evergreen and beach (104) forests are somewhat similar, with neither resembling the curve for the mangrove forest. The Richards plots, from which these curves were derived, indicate that the mangrove forest consisted of a majority of tall trees (of nearly equal height) and a minority of much shorter trees. The other two forests were

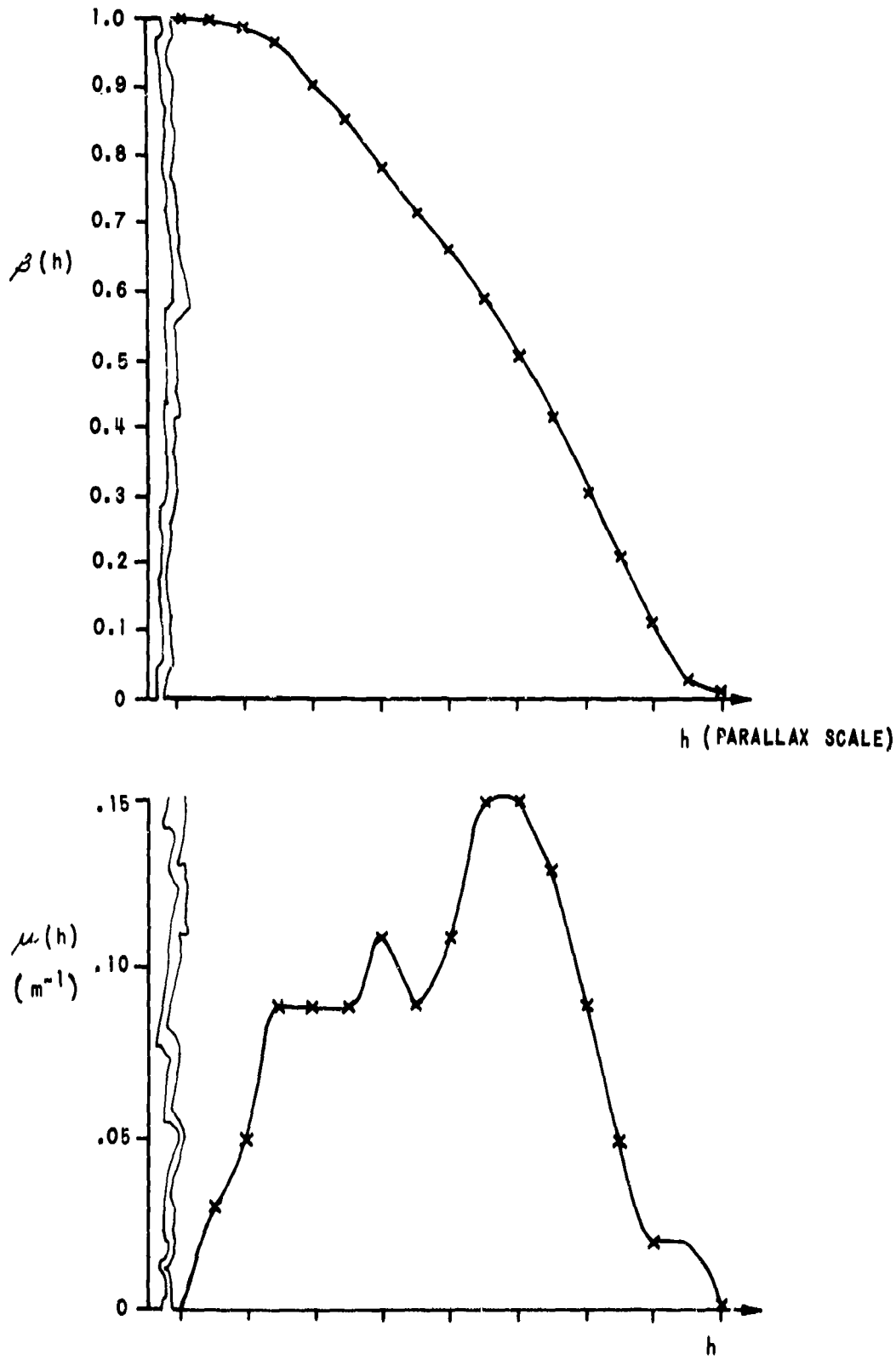


Figure 10 β AND μ CURVES FOR A 200 m LONG FOREST CANOPY PROFILE

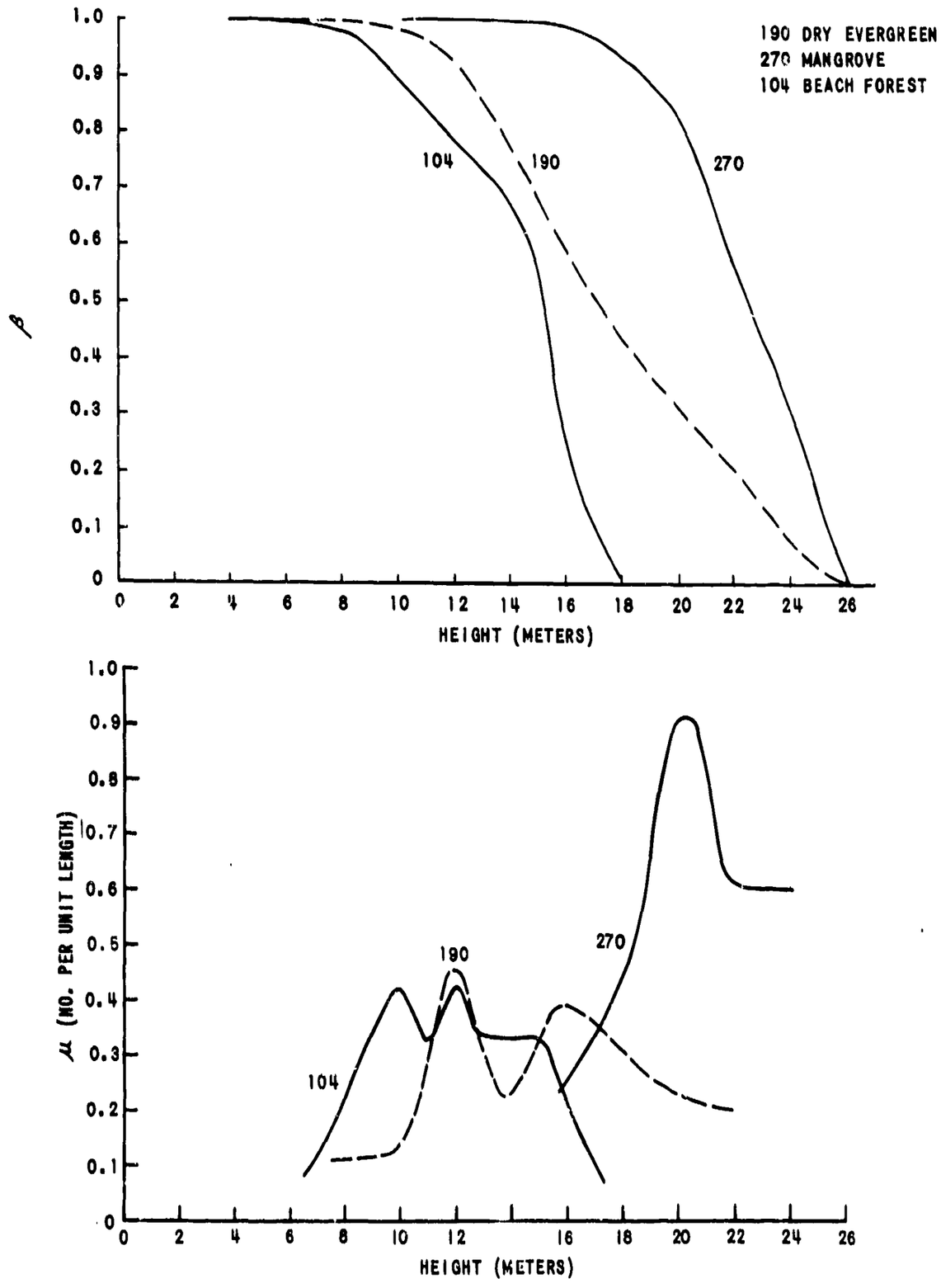


Figure 11 β AND μ CURVES FROM RICHARDS PLOTS

characterized by a minority of tall trees of variable height and a majority of shorter trees. Therefore, the single high-frequency peak in the μ curve--as well as the high values of the β curve--for the mangrove forest reflects a rather uniform canopy with a fairly uniform distribution of trees. The multiple peaks in the other two μ curves reflect the multi-storied nature of those forests.

C. Proposed Forest Classification System

The analytical methods discussed in the previous section indicate that the crossing statistics method is the most useful for describing the upper surface of the canopy. The success in relating the rather crude β and μ curves to the three Thailand forests they represent encourages one to establish a forest classification procedure based on the characteristics of the curves.

First, one would like to have height above the ground measured in normalized units, so that the β and μ curves for different forests can readily be compared with one another. Although there are several possible heights that could be chosen as the reference height, one that seems to be reasonable is the height at which a given β curve has a value of 0.5. The normalized height, H^*, for a given height, h, is then defined as

$$H^* = \frac{h}{h_{\beta = 0.5}}$$

In Figure 12 the β and μ curves for the Thailand forests have been replotted as a function of H^*. Also included in the figure are idealized curves for three hypothetical forests. The forest with the "smooth closed" canopy exhibits a nearly vertical β curve at $H^* = 1.0$ and a narrow, tall, μ curve centered about $H^* = 1.0$. In the limit, a forest having a perfectly flat canopy top would have a square β curve (that is, β remains 1.0 from $H^* = 0$ to 1.0, decreases to 0 at $H^* = 1.0$ and then remains 0 for heights greater than 1.0); the μ curve would be an infinitely tall spike at $H^* = 1.0$.

The two remaining β and μ curves represent idealized conifer forests. The closed forest is imagined to consist of a number of isosceles triangles

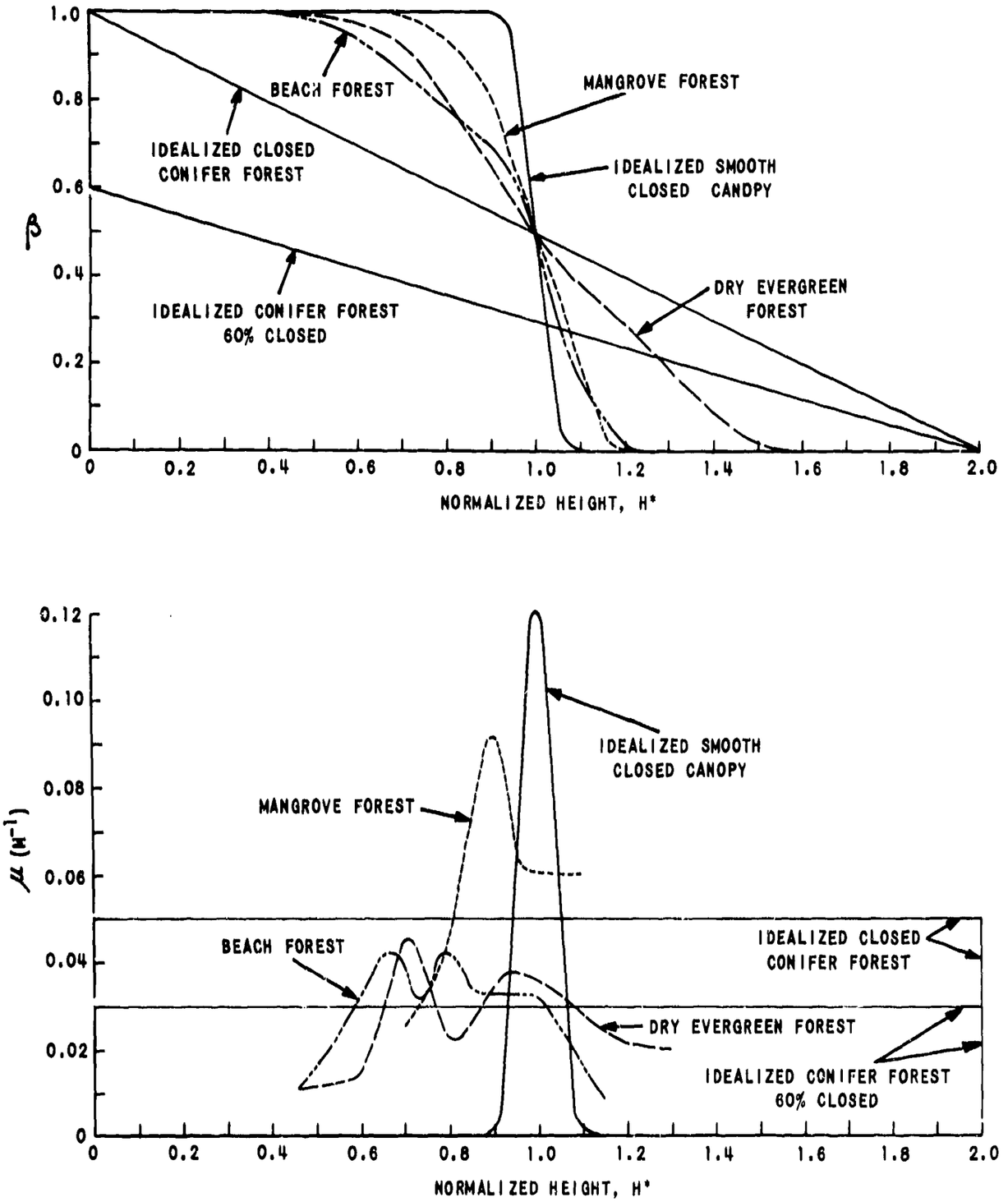


Figure 12 β AND μ CURVES AS FUNCTIONS OF NORMALIZED HEIGHT ABOVE GROUND

of the same height and extending all the way down to the ground. They are positioned such that the bases just touch each other. The β curve--the fraction of a horizontal line below the canopy profile--then decreases linearly from 1.0 at the ground to 0 at $H^* = 2.0$. The μ curve--the number of times that a horizontal line of given length intersects the canopy profile--has a constant value (here arbitrarily chosen as .05 m^{-1}) from the ground to the top of the canopy ($H^* = 2.0$), above which level μ is zero.

The influence of canopy closure on the β and μ curves is indicated by the lower conifer forest curve. If one were to remove 40 per cent of the "trees" from the forest, the curves in Figure 12 would result. Note that the intercept of the β curve with the ordinate is a direct measure of canopy closure; at $H^* = 0$ the β curve extends vertically from 0.6 to 1.0. The β curves for actual forests would not be linear at low heights and therefore the linear portion of the curves would have to be extrapolated to zero height in order to determine the closure.

In addition to being able to determine canopy closure, a β curve indicates the shape of the canopy. In Figure 12, the curves with the steeper slopes (that is, idealized smooth canopy and mangrove forest) represent the smoother canopies. The saw-tooth character of the idealized conifer forest clearly represents the roughest canopy. Therefore the mean slope of the β curve is related to the geometric shape of the crowns.

The μ curves suggest that both their amplitude and width are related to the irregularity of the canopy. The smoother canopies (idealized and mangrove) have amplitude curves that are tall and narrow, whereas the more irregular canopies (such as beach, dry evergreen and idealized conifer) have curves which are smaller in amplitude and considerably wider. The extreme width of the conifer forest is a consequence of the depth (top to ground) of the open spaces between trees. The μ curves for the beach and dry evergreen forests are wide because of the multi-storied nature of the canopy. In effect, that portion of each story visible from above has its own amplitude curve centered about a particular height and it is the sum of the individual curves that results in the measured μ curves.

The above discussion suggests that β and μ curves provide the following information about a forest canopy:

β - canopy closure (intercept of extrapolated linear portion of the curve) and geometric shape of profile (slope of curve)

μ - canopy irregularity (some function of both amplitude and width of curve)

It is not clear at the present time how the three canopy characteristics itemized above relate quantitatively to the Environmental Index. The relationship cannot be specified until meteorological and canopy measurements have been made in a number of forests under a variety of meteorological conditions.

The process of making canopy height measurements from aerial stereo-photographs is laborious and time-consuming. With an eye toward the eventual need for determining forest characteristics on an operational basis, it would seem feasible to consider a height-finding device such as a laser radar. A laser radar has the advantage that it can be flown over a canopy and provide a real-time read-out of the vertical distance between the aircraft and the upper surface of the canopy. Since a laser beam is very narrow, the beam would pass through canopy openings frequently enough to determine the height above the ground of all canopy measurements. A laser radar has an additional advantage in that the approximate density of the canopy can be determined by the average fraction of the returned signal received from various levels below the canopy top.

VII. TEST OBJECTIVES AND OUTLINE OF RECOMMENDED TESTS

A. Test Site Selection

Development of the concepts introduced in the preceding Chapters into a readily applied forest analog classification system requires testing and collection of forest data from a variety of forest environments. A two phase testing program is recommended. First, a limited number of tests should be conducted in which fairly extensive diffusion, meteorological, and forest measurements are made. The objective of these tests will be to refine the relationship between Environmental Index and ventilation rate, and to determine other relationships between diffusion properties and environmental parameters (both meteorological and forest measurements). The second phase of testing should include a much greater variety of forest types and number of tests, but the tests themselves can be quite simple and include only forest and standard meteorological measurements. The second-phase tests have as their objective the development of general relationships between readily obtained forest data and the numerical Environmental Index.

The conduct of actual diffusion tests in a large number of forest types, and for a range of meteorological conditions in each forest, obviously presents an extremely large testing requirement. On the basis of the ideas and results presented in this report, we believe that it is much more efficient to pursue a two-phase program, where the basic physical forest effects are evaluated in detail in a few representative forest types, and the general classification system is filled in by much more limited measurements involving many forests. The specific testing recommendations presented here are for the Phase I tests. Phase II test requirements can best be defined in detail after initial results from the first phase have been analyzed.

It is recommended that diffusion tests be carried out in at least five--if possible, six--different types of tree stands that represent reasonable extremes of canopy roughness and closure, and vertical and horizontal permeability. General descriptions of the six recommended forest types are given below.

1. An irregular-canopied, variable-height, closed stand of broadleaf trees (ideally a tropical jungle site).

2. An irregular-canopied, uniform-height, closed stand of coniferous trees (ideally a boreal forest of the European spruce forest type).

3. A smooth-canopied, uniform-height, closed stand of broadleaf trees (ideally an old tropical plantation).

4. An open--50% or less--uniform-height stand of coniferous trees (ideally a subarctic spruce stand) with openings or clearings of various sizes.

5. An open--50% or less--uniform-height stand of broadleaf trees (ideally a subarctic aspen or birch stand, or mid-latitude equivalent) with openings or clearings of various sizes.

6. A second open, uniform-height stand of broadleaf trees with heavy undergrowth (ideally an open tropical plantation that has been abandoned or poorly managed) preferably with openings or clearings of various sizes.

All stands should contain their natural undergrowth with as little disturbance as possible and the terrain for all should be as flat as practical. The flexibility of site choice is between site 5 and 6. Use of both sites would be most desirable, although the most important test objectives could be satisfied with either. Site 6 would provide more insight into the influence of undergrowth.

The rationale for the choice of test sites is based on the need to establish the effect of the basic forest influences: canopy roughness, canopy permeability, and undergrowth density. The recommended test-forest types encompass a wide range of each of these forest characteristics, and will therefore make it possible to determine the overall effect of gross differences in roughness, permeability and density of crown and undergrowth. The total

range of meteorological and diffusion effects will determine the operational significance of the influence, provide guidelines for deciding on the refinement necessary in measurement of related forest characteristics, and provide a basis for the planning of additional tests needed for practical analog specification. In site selection, emphasis has been placed on canopy irregularity, with canopy permeability secondary and undergrowth tertiary in importance.

The test sites for each of the recommended forests should cover an area of at least 1200 meters along the prevailing wind direction and 500 meters across the prevailing wind. Forested areas of roughly similar characteristics should surround the test site for at least several hundred meters on all sides, and several thousand meters upwind. While the type of trees, closure, etc. need not be characteristic of the test site in this surrounding area, it is important that no abrupt discontinuities in tree height or coverage exist.

The instrumented test grid for aerosol sampling should be located at the downwind end of the forest site. A test grid of approximately 400 x 400 meters is recommended.

B. Aerosol Diffusion Trials

We recommend that similar aerosol diffusion trials be conducted at each of the test sites with similar meteorological and sampling instrumentation. The most informative type of trials for this study would be continuous line or point source releases above the canopy and continuous (non-thermal) point source releases below the canopy (1.5 m above the ground). The principal advantage of continuous sources is that the results integrate over the short term turbulent fluctuations that have caused such wide trial-to-trial variability in previous tests with instantaneous sources. Such integration reduces the number of trials necessary for a given level of statistical confidence in the results, and allows better identification of the influences of trial-to-trial variation in mean wind and stability conditions. Furthermore, continuous sources allow better control of aerosol concentrations to avoid sampler saturation near the source or insufficient sample size downwind.

The aerosol used for the tests is not critical so long as the same material is used for all tests. FP, BG, or a similar simulant (or aerosols of concern to DTC) would simplify the selection of sites and running of tests. A simulant that does not adhere to the leaves would eliminate this complication from the test analysis if such a simulant is available and readily sampled. A primary consideration in the choice of aerosol is the ability to make short interval dosage measurements that are necessary to evaluate the time dependent relationships outlined in Chapter II.

C. Meteorological Measurements

The minimum meteorological instrumentation needed for reliable analysis should consist of at least:

1. Two instrumented towers (one at the location of aerosol release and one near the downwind end of the sampler grid).

2. Each tower instrumented to acquire wind speed and direction, vertical motion, and their standard deviations at:

a. 10 meters above the canopy ——— (This level is chosen because it corresponds to the internationally accepted anemometer level for "surface wind" measurements)

b. 2 meters above the canopy

c. at canopy level

d. 2 meters below the canopy

e. approximately 2 meters below the lower canopy

f. 1.5 meters above the ground

3. Each tower instrumented to acquire temperature or the temperature difference from some standard level at:

a. all levels where wind is measured

b. an additional level as close to the ground as practical with the sensors used

4. One tower should contain a remote reading instrument for monitoring solar radiation (an Epply pyrheliometer or comparable optical wavelength sensor) at the highest level on the tower.

5. A movable wind sensor of the same type used at the lower tower level.

6. A movable light sensor of the same type used on top of one tower.

It is realized that the bivanes presently used are incapable of accurately measuring the light air motion within a dense stand (44, 61, 92). Because of the vital importance of the information to be gained from such measurements, it is highly recommended that other air motion sensors be developed and tested for use in and below the canopy. Sonic and hot-wire anemometers (such as those that have been used by ecologists, 6, 30, 34, 41, 53, 55, 96, 98) should be evaluated. If complete sets of three orthogonally mounted sensors are not feasible, a single hot-wire anemometer might be utilized to measure the variance of horizontal flow; a single sonic anemometer could be used to measure the extremely important vertical component of motion averaged over a short vertical path. In the absence of suitable wind instruments, bivanes should be locked into a horizontal position for use as anemometers and wind vanes for below canopy observations. In such a case, only mean wind and a biased estimate of horizontal turbulence can be obtained below the canopy, and insight into below-canopy air motion would be drastically reduced.

The movable wind and vertical motion sensor and the light sensor should be used to make several areal surveys of light and air motion at various locations over the aerosol sampling grid for comparison with tower measurements. Ideally, a number of separate wind and vertical motion sensors should be strategically located at various sites on the grid to acquire simultaneous air motion measurements. The single air motion sensor is a compromise that can substitute for the instrument array if frequent measurements are made under a variety of ambient meteorological conditions, as well as at a variety of locations.

All trials should be run with an ambient wind speed of from 2 to 8 m sec^{-1} (above canopy) but should cover the stability range of stable, neutral, and unstable temperature lapse rates above the canopy, with an absolute

minimum of three trials in each category. If simultaneous above- and below-canopy continuous source aerosol releases are made, only nine aerosol trials per test site would be required, though additional redundancy would be desirable.

The meteorological instruments should be operated under as wide a variety of ambient meteorological conditions as possible when aerosol trials are not in progress. Variable ambient wind directions will provide different wind fetches for the above-canopy air motion sensors and therefore a variety in canopy roughness upwind of the sensors. Thus, each test site can provide a number of comparisons between measured canopy irregularity (from aerial photographs or laser radar) and above-canopy air motion to help determine this important relationship. Variable ambient wind speeds will provide the data necessary to establish the interrelationship between ambient wind speed, canopy level air motion, and momentum penetration into the stand. Through such observations, substantial information can be gained with a relatively modest experimental effort.

D. Tree Stand and Vegetation Measurements

The recommended tests will require careful and extensive measurement and assessment of tree stand and vegetation characteristics. A number of vegetation measurements are outlined in Appendix B. Of these, 1) stereo-pair aerial photographs or laser radar height measurements, 2) crown vertical transmissivity measurements at each of several locations over the grid (including the two tower locations), and 3) measurements of horizontal obstruction (at crown level, just below the crown and at approximately 1.5 meters above the ground) comprise a minimum of tree stand and vegetation measurements for adequate evaluation of the stand character-cloud behavior relationships.

E. Conclusion

The brief test outlines given above provide the basis for a series of meaningful diffusion experiments that we believe can result in quantitative definition of the most significant forest-diffusion relationships. They should

provide relationships between diffusion properties and the meteorologically-defined Environmental Index, and also a basis for specifying the Environmental Index from measurements of physical forest characteristics.

Detailed experiment design for each of the five basic test series must be done after test sites have been chosen, meteorological instrument and aerosol sampler limitations are specified, and site logistics are known. We recommend that the initial test serve as a vehicle for evaluating improvements in experiment design and instrumentation. Accordingly, an accessible site should be chosen and the site should be over-instrumented to provide detailed meteorological and diffusion data. Several different instruments for measuring some parameters can be compared to determine the most suitable type for future field programs. In this way, guidelines can be established for design of efficient tests in more remote locations.

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APPENDIX A
BASIC FOREST INFLUENCES

A. General Influences of all Tree Stands

The influence of a forest on its environment arises from a modification of the ambient meteorological conditions through complex interactions between the vegetation and the meteorological conditions themselves. As a consequence of this interaction, the effect of an individual tree stand on air motions is not purely a function of vegetation, but varies strongly with ambient meteorological conditions.

Figure A-1 shows an example of variation in the forest influence with changes in the extrasylvan meteorological environment for a particular tree stand. In this example, the decrease in wind speed due to the presence of the tree stand changes substantially with differences in above-canopy thermal stability and ambient (24 m level) wind speed. Note that under stable thermal conditions, with an above-canopy wind speed of 5 mph the wind speed within the forest is 0.5 mph, while a 0.5 mph wind speed above the canopy also results in a 0.5 mph speed within the stand. This tendency for wind speed within a tree stand to remain light despite ambient wind speed is possibly the most fundamental forest influence. Differences in stand character do not change this tendency except in degree. This is also true of the effect of ambient thermal stability. For any given above-canopy wind speed, the 2 m wind speed decreases with increasing thermal stability above the canopy, but the stability effect decreases with decreasing wind speed to the point where, at low speeds, the effect is almost negligible (see Figure A-1).

In most cases the air motion within a tree stand is a consequence of the ambient meteorological conditions (air motion, thermal stability, and atmospheric pressure) outside of the stand. Pressure gradients within the stand, associated with either large-scale synoptic pressure fields or local thermal

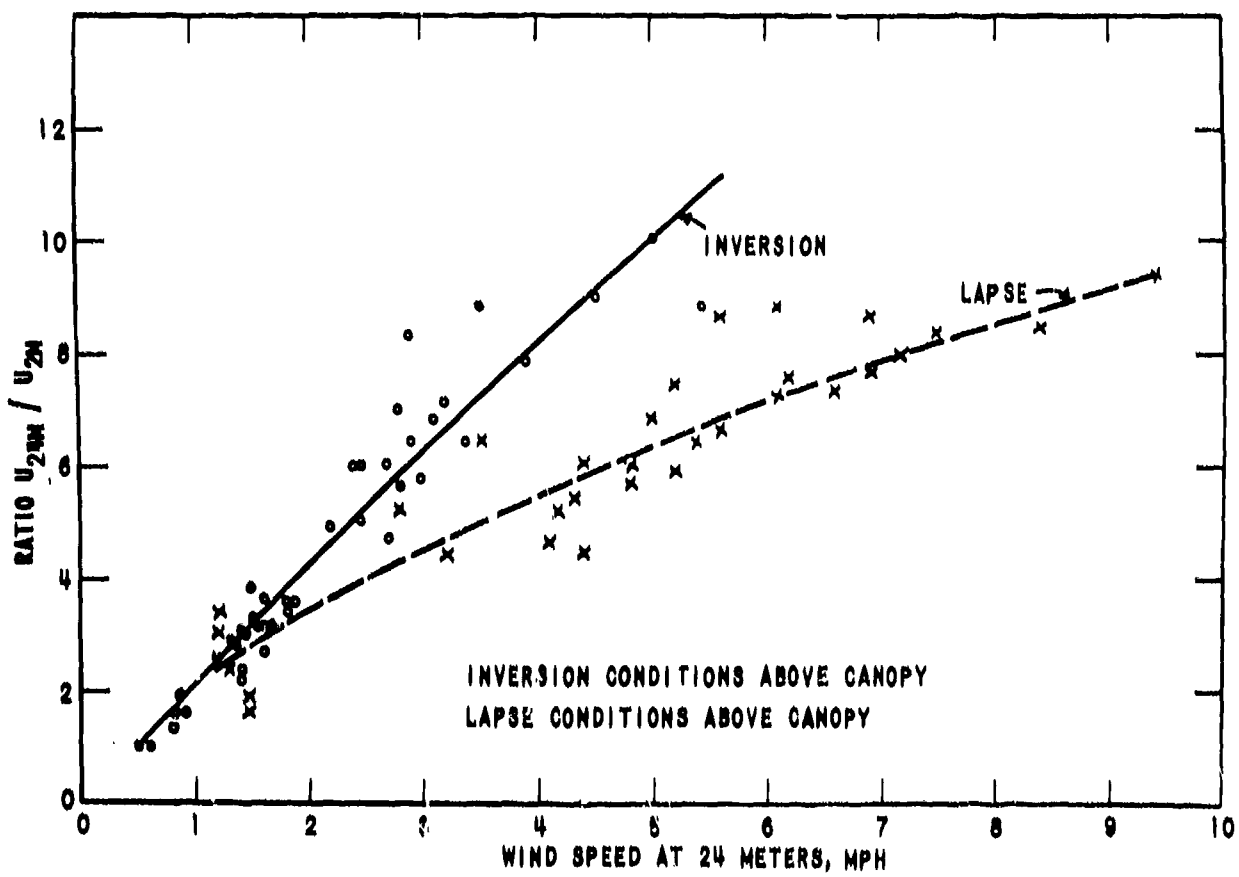

Figure A-1 THE EFFECT OF WIND SPEED AND ABOVE-CANOPY STABILITY ON THE RATIO OF AMBIENT (24m) TO FOREST (2m) WIND SPEED IN A 16.5m HIGH TROPICAL JUNGLE (FROM REF. 55)

and terrain features, may be significant in determining below-canopy winds in many situations. Similarly, border effects at stand edges or near large clearings can strongly influence local air motions. However, in general these influences are secondary to those resulting directly from downward transport of momentum from the ambient flow into the tree stand.

The vertical distribution of forest elements causes at least two, and sometimes more, different turbulence and diffusion regimes in various layers above and within a tree stand as downward momentum and turbulent energy fluxes are altered by the layers of the forest. The air motion in any particular layer, except above the canopy, is a function of both the vegetation in the layer and the nature of the flow in adjacent layers. In the air layer above the canopy, the ambient air motion is determined through interaction of the large-scale flow field with the roughness or irregularity of the canopy, but it is influenced by the thermal stability present (in itself a function of the canopy properties as well as ambient meteorological conditions). These influences reduce the wind speed and change the turbulence properties of the air above the crown-space. Horizontal motions are further reduced and modified in character at the crown top by the obstruction to motion imposed by the tree crowns themselves. Below the crowns in the trunk space (where the foliage is usually less dense than in the crown) the air motion is determined by the momentum flux reaching this level from above and the vegetation present in this layer. Finally, the portion of the momentum flux which exists at the bottom of these layers results in air motion in the ground space (from the surface to the top of the ground cover) where the last of the momentum is transferred to the vegetation and ground.

An absorption of momentum, or effective reduction in downward flux in any layer of a tree stand, reduces air motion in all lower layers regardless of the vegetation characteristics within the lower layer. Thus the behavior of an aerosol cloud within a forest is influenced by the meteorological conditions and the character of the vegetation in the layers above the cloud, as well as by the vegetation volume through which the cloud is moving. As a matter of fact, the upper portions of a tree stand (canopy and crown space) generally exert a more pronounced influence on the mean wind and turbulence beneath

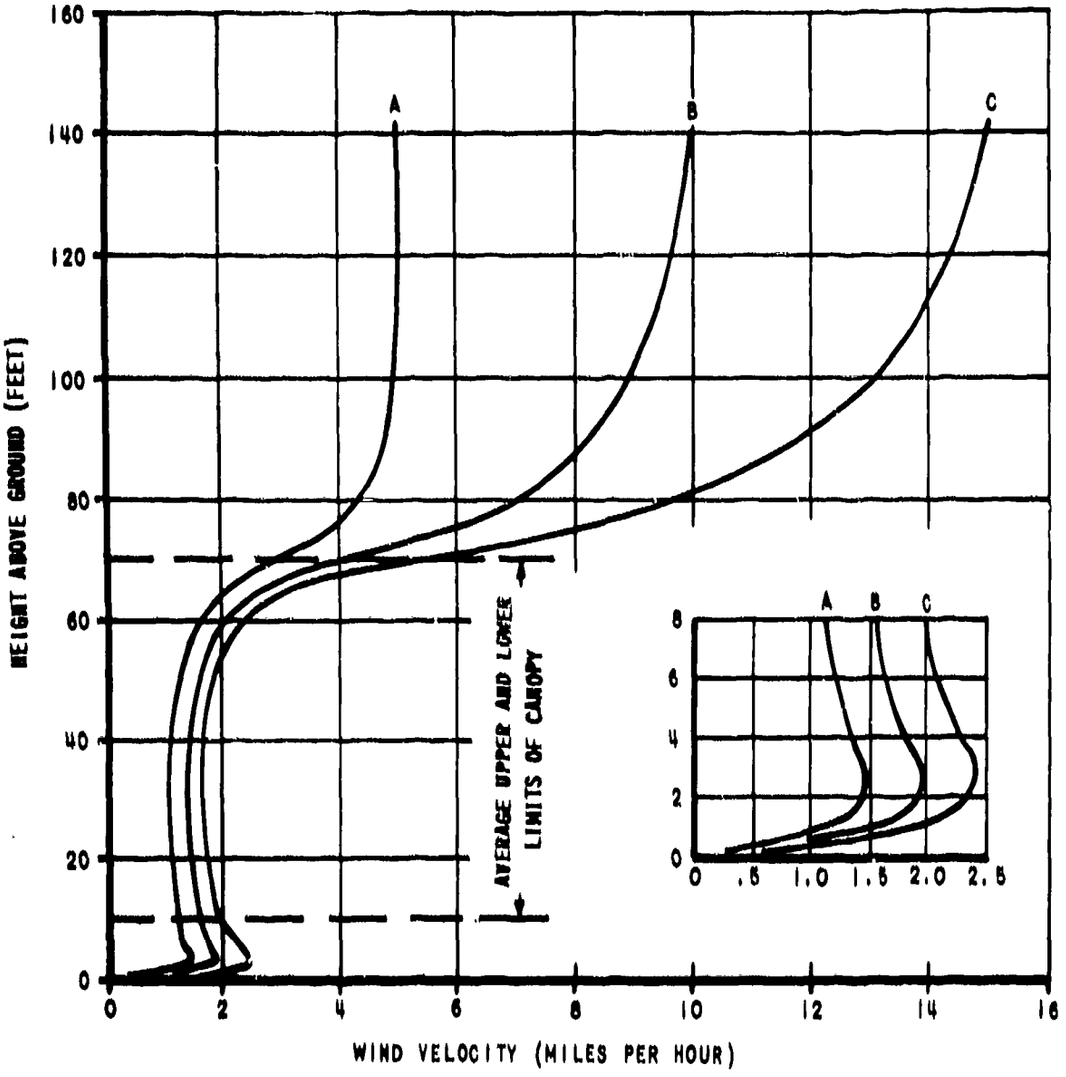

Figure A-2 THE VERTICAL DISTRIBUTION OF MEAN WIND SPEED UNDER VARYING AMBIENT WIND SPEEDS FOR A 70 FOOT HIGH STAND OF PONDEROSA PINE (FROM REF. 33)

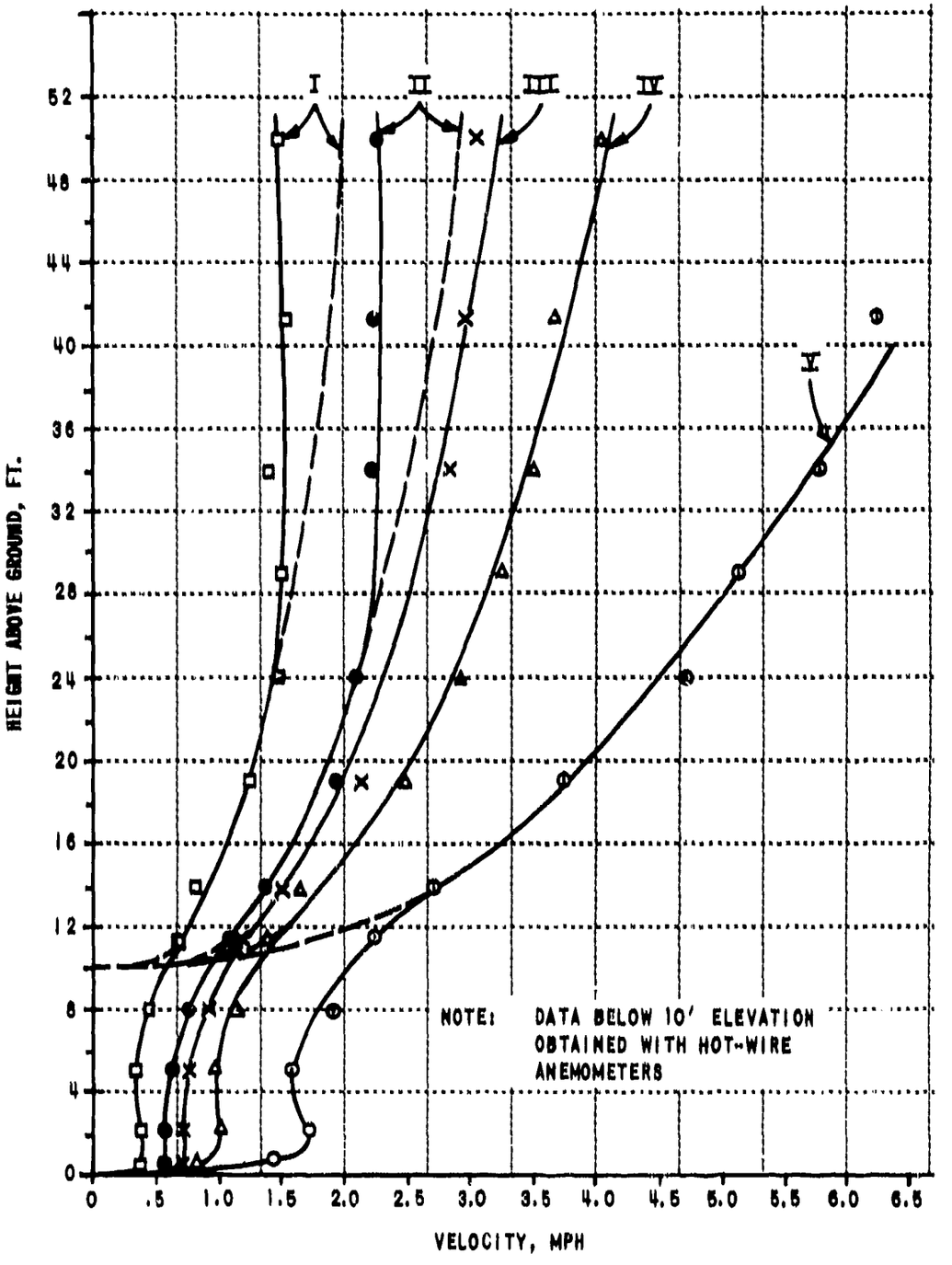

Figure A-3 THE VERTICAL DISTRIBUTION OF MEAN WIND SPEED UNDER VARYING AMBIENT WIND SPEEDS FOR AN 11 FOOT HIGH ORANGE ORCHARD (FROM REF. 53)

the canopy (and consequently aerosol cloud behavior) than does the vegetation within the lower layers. Figures A-2 and A-3 show two examples of vertical profiles of wind from two widely different types of tree stands under various ambient wind speeds. Figure A-2 contains profiles for a 70 foot high stand of Ponderosa Pine while Figure A-3 refers to an 11 foot high orange orchard. In both, the maximum decrease in wind speed occurs from about 30 feet above the canopy to canopy level, with a lesser decrease in the upper few feet of the canopy, and relatively uniform winds within and below the canopy.

B. Dominant Forest Influences

Both observational and theoretical evidence indicate that there are three forest properties that most strongly and directly affect air motion and diffusion. These are basically mechanical influences that act in combination with the thermal effects resulting from the forest's modification of the surface temperature distribution. These three may be described as: 1) irregularity or roughness of the canopy top, 2) resistance to vertical transfer provided by the canopy, and 3) resistance to horizontal transfer provided by various layers of the forest.

In the following discussion, the terms vertical permeability and horizontal permeability are used as general terms to express the qualitative forest influences listed as numbers 2 and 3 above. The property usually chosen to illustrate these influences is the horizontal momentum, since more data are available for horizontal wind than for any other property. It should be understood that the same treatment can be applied to the transfer of aerosol concentration or other properties of the air.

1. Canopy Irregularity or Roughness

The term "canopy" as used herein refers to the upper surface of a tree stand directly exposed to environmental conditions, and includes forest openings and clearings as well as the irregular height and shape of tree crowns. Canopy irregularity can be considered the primary forest influence because it causes the most direct modification of above-canopy motion and exerts an influence that is equal to or greater than the other two basic stand properties. This influence is two-fold: thermal and mechanical.

Sunlight incident on a canopy increases the temperature of the upper foliage, causing decreased thermal stability above the canopy and increased thermal stability below. Nocturnal radiational cooling in a forest also occurs at the canopy level and lowers the temperature of the upper foliage. This causes a stable thermal lapse rate above the canopy and a neutral to unstable lapse rate below. Figure A-4 shows an example of the change in vertical temperature profile as a consequence of the absorption and loss of heat at canopy level. The line at 45 feet in Figure A-4 represents mean canopy height. The effect of solar radiation is most pronounced in the 12:08 and 14:02 profiles. The effect of nocturnal cooling is pronounced in the 22:08, 01:02, 03:58 and 06:13 profiles. The lowest temperature does not occur at the canopy under nocturnal cooling, because the cold air tends to sink through the crown space to the extent that canopy permeability allows. The profiles in Figure A-4 were observed in a closed tropical jungle and the cold air was able to penetrate only a short distance into the crown space. A less dense stand would reveal a more nearly isothermal lapse rate beneath the canopy since cool air can drain to the ground.

When a canopy is irregular or contains a number of openings, solar radiation is absorbed through a greater depth and the temperature maximum is broader and of smaller magnitude; thus thermal stability offers less impedance to vertical momentum transfer than in a dense uniform canopy. At night, a more irregular canopy or open stand radiates from many levels so that all levels share in the cooling, and the stable temperature lapse rate above the canopy is less pronounced than over a closed crown. The effect on momentum transfer of such differences in stability of the air layer above the canopy is evident from Figure A-1.

The mechanical effect of canopy irregularity is a reduction of the mean wind at a given level near the canopy top and an increase in vertical motion and downward momentum transfer at the canopy. These effects are due to an increase in turbulence in the air layer above the canopy. In general, the more irregular the canopy the more turbulence is created for a particular above-canopy wind speed and stability. The scale of turbulence above the

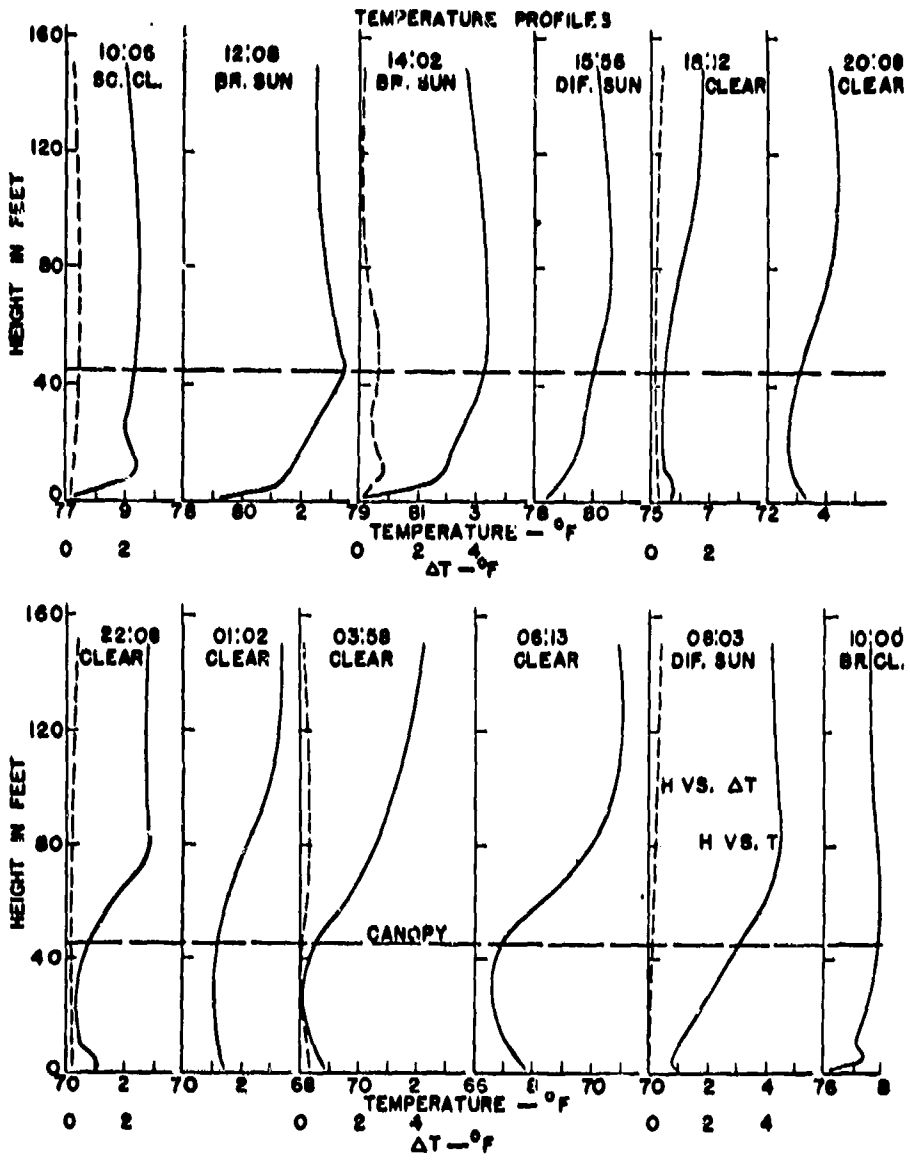

Figure A-4 THE VERTICAL DISTRIBUTION OF TEMPERATURE FOR A PANAMANIAN JUNGLE SITE WITH 45 FOOT HIGH CANOPY (FROM REF. 41)

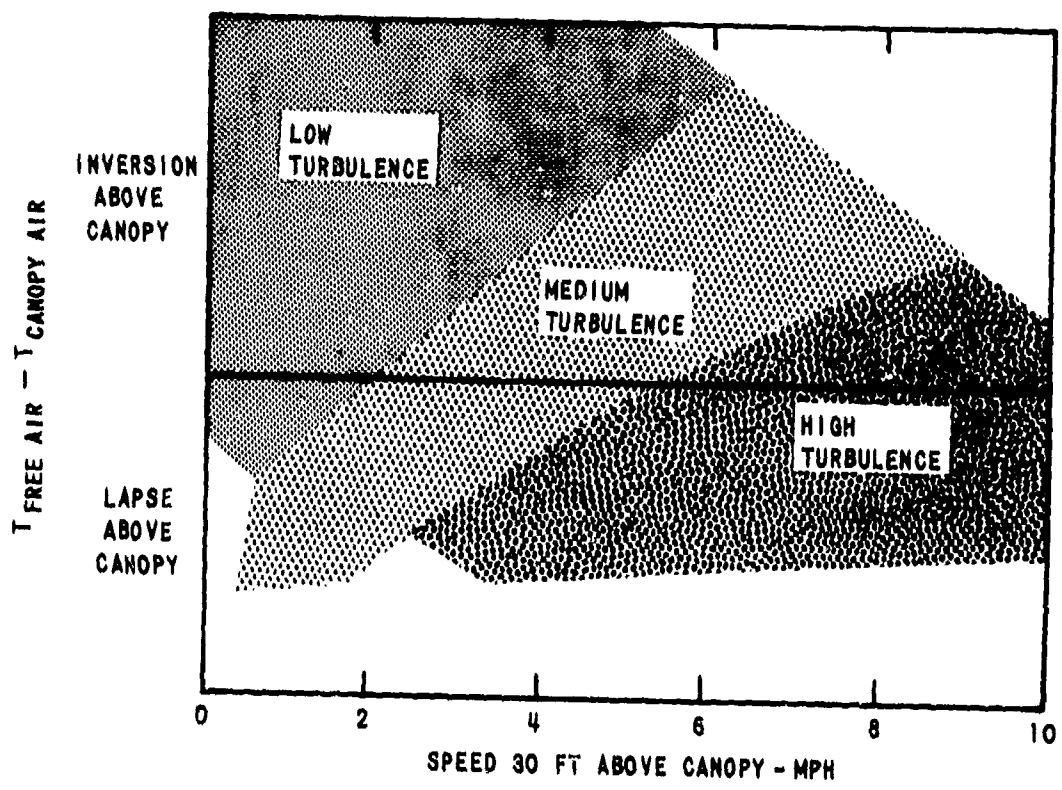

Figure A-5 THE RELATIONSHIP BETWEEN TURBULENCE (MEASURED 6 FEET ABOVE THE GROUND) AND ABOVE-CANOPY THERMAL STABILITY AND AMBIENT WIND SPEED. (FROM REF. 55)

canopy is also influenced by canopy irregularity; the greater the height differences of the canopy and the larger the tree crowns that make up the canopy irregularity, the larger the scale of induced turbulence.

Figure A-5 illustrates the combined influence of mean wind and above-canopy stability on turbulence beneath the canopy. From the figure it appears that unstable above-canopy lapse rates and/or strong ambient winds act (along with an irregular canopy) to induce strong turbulence above the canopy and greater momentum flux into the crown space below. On the other hand, a smooth canopy, above-canopy temperature inversion, and/or light winds can reduce the canopy-level turbulence to the point where little or no momentum is transferred downward into the forest, and little or no air motion is found there, regardless of vertical or horizontal permeability.

2. Canopy Permeability

Canopy permeability and thermal stability in the crown space effectively control the downward transfer of momentum and the mean air motion within a tree stand. Even the most dense, closed, tropical jungle or European spruce forest canopy has a finite permeability and allows some mass and momentum transfer through the tree crowns under neutral and unstable temperature lapse rates beneath the canopy. When a stand is relatively open, the number, size and locations of openings dominate the canopy permeability to the point where individual tree crowns can often be considered as impervious obstacles without incurring serious error.

The canopy irregularity influence on above-canopy turbulence at a given location is a composite effect of the canopy geometry for a considerable distance upwind of that location. However, the influence of canopy permeability is comparatively localized in nature. The momentum transferred downward through the crown space due to the permeability of the canopy at some location is primarily influential in causing air motion beneath that location. The influence decreases with horizontal distance from the location where the momentum penetrates the canopy. Irregular distribution of effective canopy permeability leads to the frequently observed wide differences in dosage measurements from one location to another within a stand during aerosol diffusion studies.

The role of thermal stability below the canopy is nearly as great as that of physical forest structure in influencing momentum transfer. A stable inversion, such as those often formed on sunny days, can effectively block downward transport of momentum from above the canopy, even when canopy permeability itself would only reduce the transport. Such inversions often extend into small openings and restrict vertical motion despite the lack of physical obstructions to motion. Thus, as with the canopy roughness effects, consideration must be given to both the forest's direct mechanical influences and its thermal effects in determining vertical transfer.

Most of the reduction in vertical transfer tends to occur in the upper portion of the crown space. (See Figures A-2 and A-3.) The influence of vegetation "impedance" to vertical transfer is cumulative, and each successive layer of foliage contributes to a further reduction in motion. However, this reduction is not a constant for a given measure of physical obstruction. Observations show that any vegetation layer reduces the motion less when there are lighter winds and less turbulence at the top of the layer. Thus, because of the reduction of turbulent energy and mean horizontal momentum by the screening action of higher level foliage, the percent reduction in mean wind decreases with distance downward. (See Figure A-6.) As the air motion becomes less turbulent and the spectrum of turbulence shifts to shorter wavelengths, a permeable foliage layer becomes less effective in impeding the passage of air. Thus, the lower layers reduce the transfer of momentum less because the flow through them is less turbulent. This also explains in part why low mean wind speeds above a canopy (which are usually accompanied by less turbulence) result in proportionally higher speed winds below the canopy than do strong above-canopy winds.

3. Horizontal Permeability

Horizontal permeability is akin to the vertical permeability of a tree crown and exhibits the variable magnitude just discussed. In a crown where the turbulent energy is large, the obstructions to horizontal motion are more effective than at lower levels where the flow is less turbulent. In the understory beneath a closed, moderately dense crown-space the air motion is often reduced to light meandering wind, and the horizontal permeability is greater for a given density of foliage.

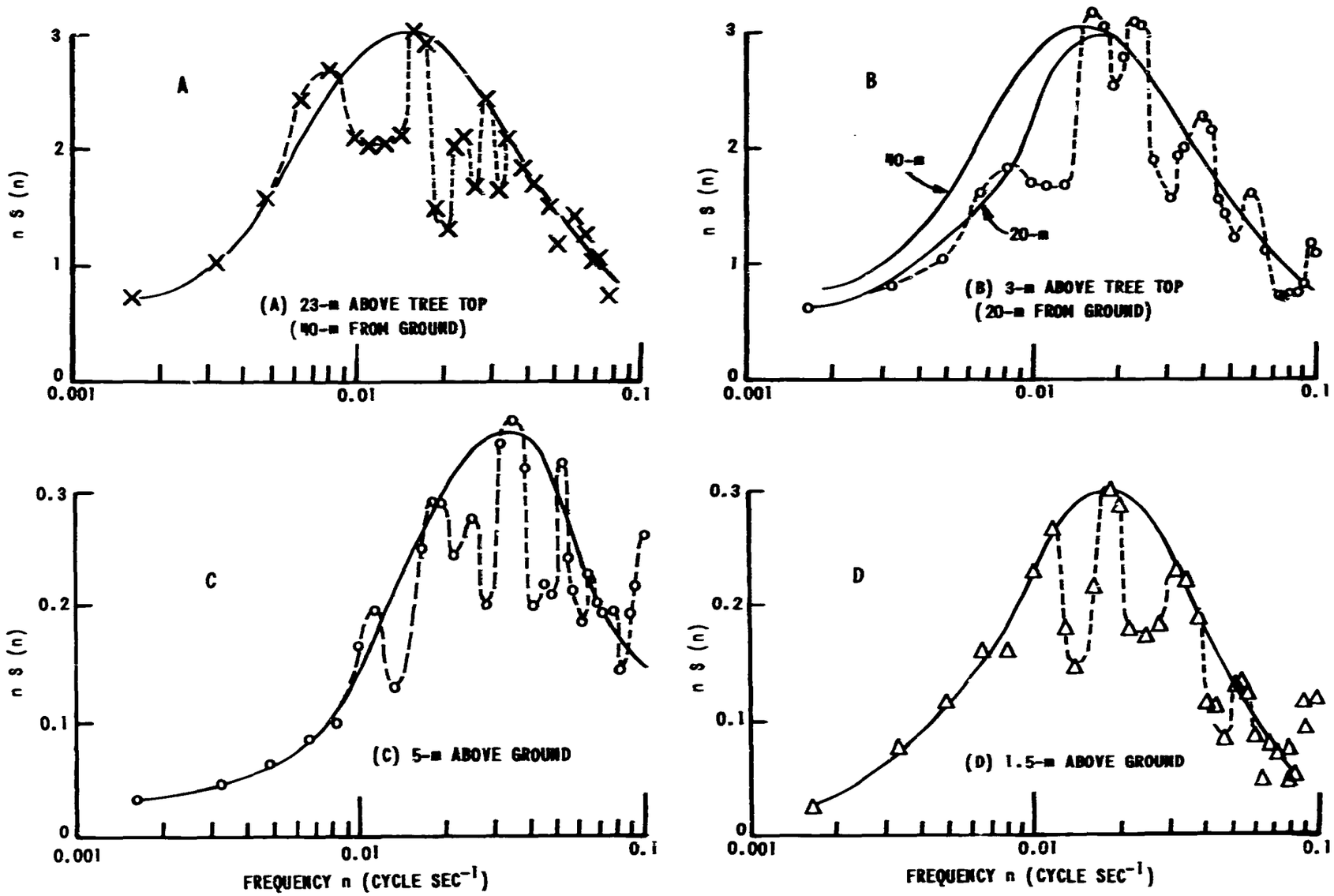

Figure A-6 THE TURBULENT ENERGY DISTRIBUTION AT FOUR HEIGHTS ABOVE AND WITHIN A DECIDUOUS FOREST IN MINNESOTA (FROM REF. 92)

Horizontal permeability is generally the least important of the three basic forest influences. However, where the canopy permeability or the wind above the canopy is great, horizontal permeability plays an important role in horizontal motion below the crown space. Figure A-2 shows an effect which can be enhanced by large horizontal permeability below the crown space. In the relatively unobstructed layer near the surface the wind speed is greater than at higher levels. This is also evident for the higher ambient wind speed profiles in Figure A-3. Horizontal permeability may be quite important in cases of large vertical permeability of the canopy, strong winds aloft, or thermal instability. Under these conditions and where openings in the canopy are present, high horizontal permeability permits horizontal transfer of air from beneath the opening to surrounding areas beneath less permeable portions of the canopy.

The direction of horizontal motion within a stand is more dependent upon horizontal permeability than is speed. Where horizontal permeability is not uniform (particularly in the vicinity of a canopy opening) this irregularity is often effective in altering the direction of the horizontal motion induced from above.

In summary, the basic forest influences on air motion and diffusion within a tree stand arise from the thermal stability modification associated with radiation from and to the sky and mechanical influences associated with canopy irregularity or roughness, canopy permeability (vertical), and horizontal permeability in the crown and trunk space. These forest influences interact with ambient meteorological conditions to determine the air motion present above and within a tree stand.

APPENDIX B
FOREST VEGETATION CHARACTERIZATION

In Chapter VI, the problem of relating the proposed Environmental Index to a given forest with a given canopy roughness, density and closure was discussed. This appendix summarizes other proposed and proven techniques which can be used to characterize canopy and subcanopy vegetation.

A. Canopy Roughness Measurement Techniques

The use of stereo-pair aerial photographs to characterize the roughness, occurrence of openings, and changes in overall height of the canopy has been demonstrated in Chapter VI and is investigated in more detail in Appendix C. Though the photogrammetric measurements of canopy height are rather laborious to obtain, the sample evaluations made along a straight line indicate that such measurements provide a practical means for determining quantitative information about the irregularity of a canopy.

Since measurements along a straight line (as opposed to measurements over an area) appear to be sufficient to describe the upper surface of the canopy, a faster and more efficient way of obtaining the same information would be particularly useful. One measuring device which fits these requirements is a laser radar.* Pointing downward from an airplane or helicopter flying at a constant altitude, the laser radar would provide a very detailed profile of the canopy. Since the laser beam would occasionally penetrate to the ground through openings in the canopy, the height of trees above the ground can be determined. Only the speed of the aircraft or helicopter would be required in order to convert the profile information from time to space units.

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*Aero Service Corp. of Philadelphia has developed an air-borne laser altimeter for use in connection with aerial photogrammetry. The altimeter profiles the top of forest canopies and needs only an occasional square foot of opening to measure distance to the ground.

B. Canopy Light Transmissivity and Closure Index

Canopy light transmissivity of tree stands has been measured by a number of different techniques because of its importance in biology and ecology. All of the techniques use some type of visible light sensor such as an Eppley pyrheliometer or Norwood Director light meter to make comparative measurements below the canopy and in the open under a variety of solar angles and cloud cover (3, 4, 6, 39, 47, 65, 67, 72, 92). These measurements are generally made at a number of locations within a stand, times of day, and degrees of cloud cover to determine an average or a representative transmissivity. The basic advantage of these techniques is that measurements are simple to make and interpret if one can make simultaneous measurements above the canopy or in a large clearing near by. The primary disadvantages are the sensitivity of readings to solar angle and cloud cover, and the need for access to a level above the canopy or a nearby large clearing.

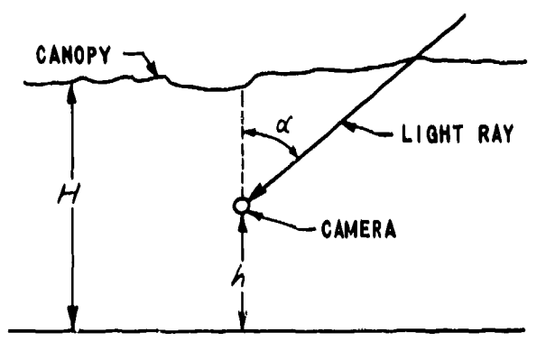
A second canopy characteristic, closely related to canopy transmissivity, is the canopy closure index (percent of canopy through which sky light cannot be seen). The term vertical obscuration is sometimes used for describing the same forest characteristic. The canopy closure index has been measured by a number of different techniques which require various levels of effort for measurement and interpretation, and various degrees of skill or subjective judgment on the part of the observer. Photographic methods (17, 18, 22, 31, 77, 89) and particularly hemispherical photographic methods (3, 23, 24, 31, 45) appear to be most suitable for closure index measurement.

Both canopy transmissivity and closure index are normally measured from one level near the ground. When measured in this way, both quantities are dependent on the distribution of total mass of vegetation. While such measurements are related to canopy permeability, much more meaningful information can be obtained if they are made from a number of different levels in the forest. Canopy closure index measurements made as a function of height provide information on both vertical and horizontal distribution of vegetation. These distributions ultimately determine vertical and horizontal canopy permeability. Furthermore, canopy closure index as a function of height appears to constitute a direct measure of the distribution of solar energy absorption (and radiation to the sky) in the forest.

For the purpose of measuring the vertical distribution of vegetation, consider an experiment in which a hemispherical camera is used to photograph the upper portion of the forest from a number of different heights above the forest floor. Let this camera use high contrast emulsions and developing techniques so that all portions of the film not exposed to direct skylight are completely transparent. With such an arrangement the integrated transmissivity of the developed negative is a measure of the fraction of the sky that is visible at the height of interest. The net transmissivities of concentric rings of the photograph provide a measure of the fraction of the sky visible as a function of elevation angle, or, alternately, the integrated extinction coefficient from the sky to the camera as a function of elevation angle. The following relationships are evident from optical theory and the geometry of the experiment, which is depicted below.

In an absorbing medium

$$I = I_o e^{-\beta x}$$



where I_o is the intensity of incident light on the medium, I is the intensity of light incident on the detector, β is the extinction coefficient defined as the fraction of the light absorbed per unit length of path, and x is the path length.

In our experiment the expression converts to

$$I = I_o e^{-\left[(H-h) \sec \alpha\right] \beta}$$

or

$$\beta = \log_e \frac{I}{I_o} \frac{1}{(H-h) \sec \alpha}$$

The quantity I/I_o is measured by the transmissivity of the concentric ring of the film at zenith angles α to $(\alpha + d\alpha)$ from the sky to height h. The vertical distribution of solar energy absorption is the derivative of β with

respect to h for the ring that corresponds to the elevation angle of the sun. Since the amount of light that is not absorbed is transmitted, the transmitted energy is proportional to $1-\beta$. The fraction of the energy radiated from vegetation that is transmitted to the sky is therefore proportional to the integral of β over all elevation angles.

C. Measurements of Horizontal Distribution of Vegetation

In a manner similar to that in which canopy closure index and canopy transmissivity are related to canopy permeability, horizontal transmissivity or visibility is related to horizontal permeability. Since horizontal light transmission is not of prime importance to forest ecology few measurements of this kind exist. The only quantitative measurement technique related to horizontal visibility that was found in the literature was that used in the AMPIRT test site studies in Thailand (17, 18, 64).

The technique consists of observation of a pair of special targets (each at a different height) by an observer at a central point as the targets are placed at ever increasing distances in various directions from the observer. The percentage of each of the targets visible to the observer at each location is then plotted as a function of distance to determine the decrease in visibility with distance. The data obtained is directly analogous to the measurements of canopy closure as a function of height that were suggested in the preceding paragraphs.

D. Gross Forest Descriptors

Forest characteristics cover the full spectrum from the scale of an individual leaf or twig to the gross characteristics of trees of a particular climatic zone. For aerosol diffusion tests, forest characteristics commensurate with the size of an individual aerosol cloud and its travel distance (such as the forest descriptors discussed thus far) are necessary to interpret the forest - diffusion relationships in detail. Of the descriptors and observations thus far covered, only those based upon aerial photography and the use of a laser radar are practical for describing forests on a scale commensurate

with the informational needs and observational capability of a combat field commander.

In practical field use only basic tree stand characteristics and measurements or estimates are available. For strategic planning, only the basic characteristics of aerosol performance in gross categories of forest types are usually of concern, and correspondingly coarse forest descriptors should suffice; see Chapter IV for examples of this situation. Thus, as we move up the scale from individual tests to broad-area planning, generalized forest descriptors and even qualitative descriptions become more relevant to the intelligence needed for predicting aerosol diffusion characteristics. For forest descriptors in the scale of medium to large area classification, we are required to turn to the sources of information on this scale--foresters, ecologists, and botanists. The problem is to relate the numerous ecological measurements, judgements, or assessments of tree stands (quantitative and qualitative) to the characteristics of tree stands pertinent to diffusion.

Canopy roughness or irregularity is related to descriptors such as tree type or variety of tree types, range of tree crown height, degree of crown closure, variety of tree crown shapes, vertical cross-section and plane view sketches of tree stands, and other descriptions that offer insight into canopy geometry. Canopy permeability is certainly related to mean canopy closure, crown depth, number of crown stories and degree of closure of each, type of trees, amount of undergrowth beneath the canopy, mean number of leaves on a vertical line, vertical stratification of vegetation, number of trees per acre, mean basal area, nearest neighbor distance and mean crown diameter. Horizontal permeability in the crown space is related to tree type, number of living trees per acre, size distribution of crowns, etc. Horizontal permeability in the trunk space is inversely related to canopy permeability because of the tendency for undergrowth to form in proportion to canopy opening.

The descriptors just mentioned have been further grouped and generalized into forest classifications such as age of stand, degree of climax of stand, and type of stand e.g. tropical rainforest, tropical tangle, tropical wet-dry broadleaf forest, temperate broadleaf forest, boreal forest, etc.

E. Summary

In summary, forest characterization is the most complex aspect of the forest analog problem. On the size scale commensurate with aerosol diffusion or munitions tests the only pertinent forest characteristics that can be estimated directly are canopy roughness or irregularity and the geometry of canopy openings. Horizontal and vertical crown permeability and undergrowth permeability are not directly observable but appear relatable to practical measurements of transmissivity, closure index, and/or visibility.

The determination of an analogy between test site information and specific tactical target forests or stands is restricted by the ability to classify the target. Stereo-pair photography and laser radar measurements offer means for determinating the two most critical parameters of canopy roughness and opening geometry, but permeability information may have to depend on ecological type descriptions from aerial photointerpretation, forward observers, or handbook information. In this instance relationships between ecological descriptors and the major forest influences must become the basis of classifying the target stand.

APPENDIX C
CANOPY ROUGHNESS MEASUREMENT TECHNIQUES

A. Decay Curve Methods

One of the classes of roughness indicators that has been studied is based on the statistics of average canopy height, where the average is taken over different sizes of sampling windows. By choosing various window sizes, numbers which are indirect functions of such things as clumping of trees, average crown size, etc. can be calculated. These methods characteristically require more calculation and produce less simply interpretable results than those to be discussed later. They have the advantage, however, of containing more of the entire canopy information and are thus likely to be more sensitive than the simpler methods discussed in later sections.

1. Variance Decay Method

Photographic film exhibits irregularities in exposure on the microscopic scale due to the finite size of the emulsion particles. These irregularities are undesirable and are spoken of as due to the grain of the film. The term grain itself is not well defined, but grain has about the same relation to film as (the not well defined term) roughness has to a forest canopy. The methods used by photographic scientists to measure and describe granularity of film can thus be adapted to the problem of characterizing forest canopy roughness.

<u>Definition</u>

Let h (x, y) be the height of the canopy above the point x, y on the ground.

Let a be the area of a sampling window of particular shape.

Denote by $H_i(a)$ the average value of h(x, y) computed

over the window a for a particular location of the window. It is evident that H is a function of window size, shape and location. If the size and shape of the window remain unchanged while the location is allowed to vary, we can compute the variance σ_H^2 of H for all locations of a window. It is evident that σ_H^2 is dependent on the window size a. The curve of σ_H^2 as a function of a will be taken as a characteristic of canopy roughness.

That different canopies will produce different curves of σ_H^2 vs a is demonstrated by considering the four profiles sketched in Figure C-1. For simplicity, a one-dimensional case has been used and the sampling window is chosen as a length.

Profiles 1 and 2 would be expected to exhibit similar roughness, since they have the same frequency and approximately the same amplitude. As is seen in Figure C-2, the two curves corresponding to profiles 1 and 2 (also numbered 1 and 2) are nearly the same. Figure C-1 indicates that profiles 3 and 4 will differ in roughness from profiles 1 and 2 and from each other. The curves labelled 3 and 4 in Figure C-2 demonstrate that curves of σ_H^2 vs a do retain this information.

The curve of σ_H^2 vs a was tested areally by performing the calculations on a 16 km x 16 km section of German terrain. The terrain had been digitized by recording elevations from contour maps on a 100 m square grid; the digital data were recorded on magnetic tape. It is felt that the irregularities exhibited by terrain are more nearly characteristic of those present in a forest canopy than the sine waves and triangles used above. The results of the calculations are shown on the graph of curve 1 in Figure C-3. It is seen that the variance decays with increasing (square) window size, as expected. Further it should be noted that the curve does not have complex variations, indicating that variance decay curves of complicated surfaces are themselves fairly simple.

Variance decay curves were produced for a profile and for several areas from a digitized section of AMPIRT forest canopy in Thailand. Photographs of the canopy may be found in Ref. (17). The areal digitization was done according to a statistical sampling plan developed in the following way. Budget

Figure C-1 SIMPLIFIED PROFILES

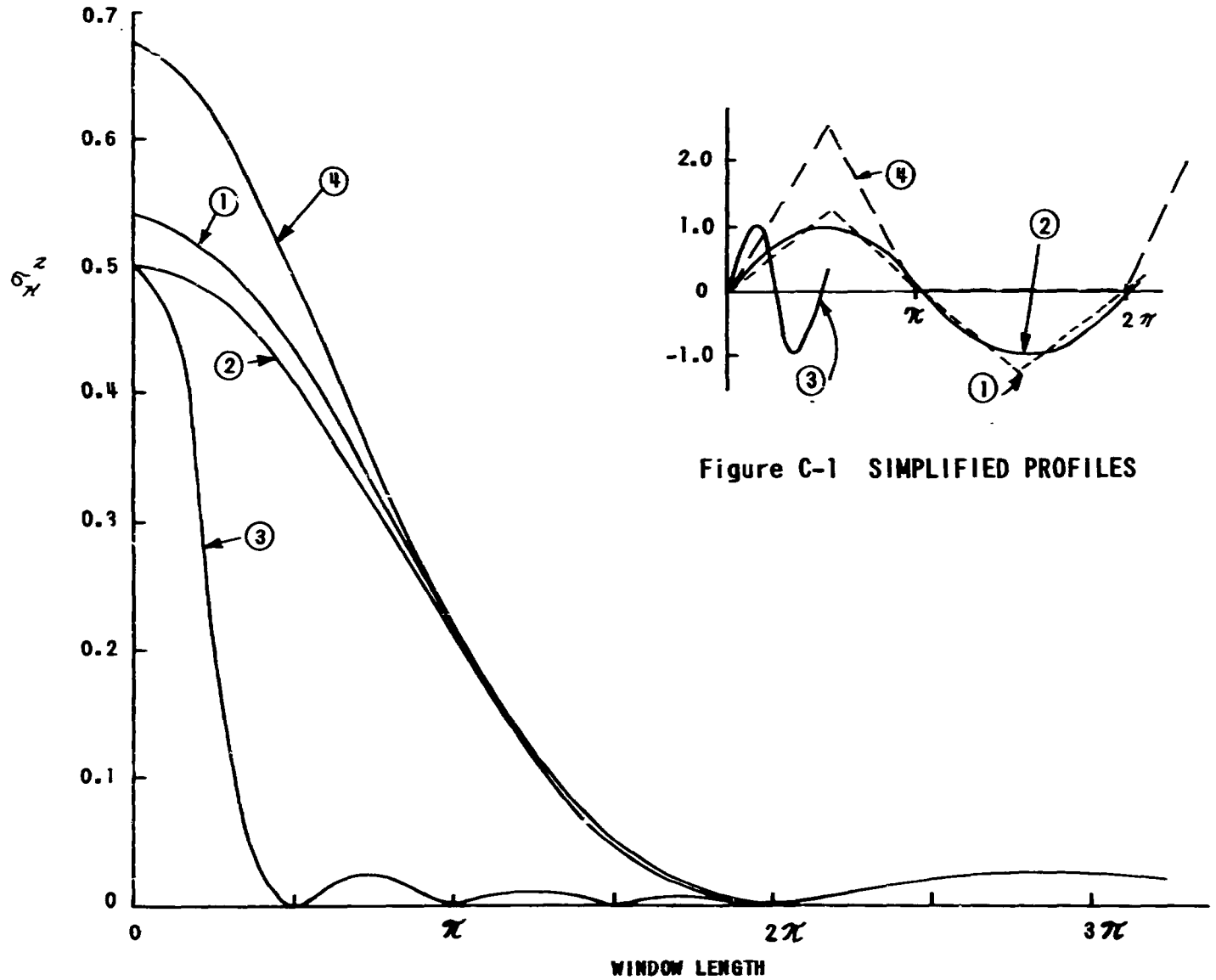


Figure C-2 VARIANCE OF HEIGHT AS A FUNCTION OF WINDOW SIZE

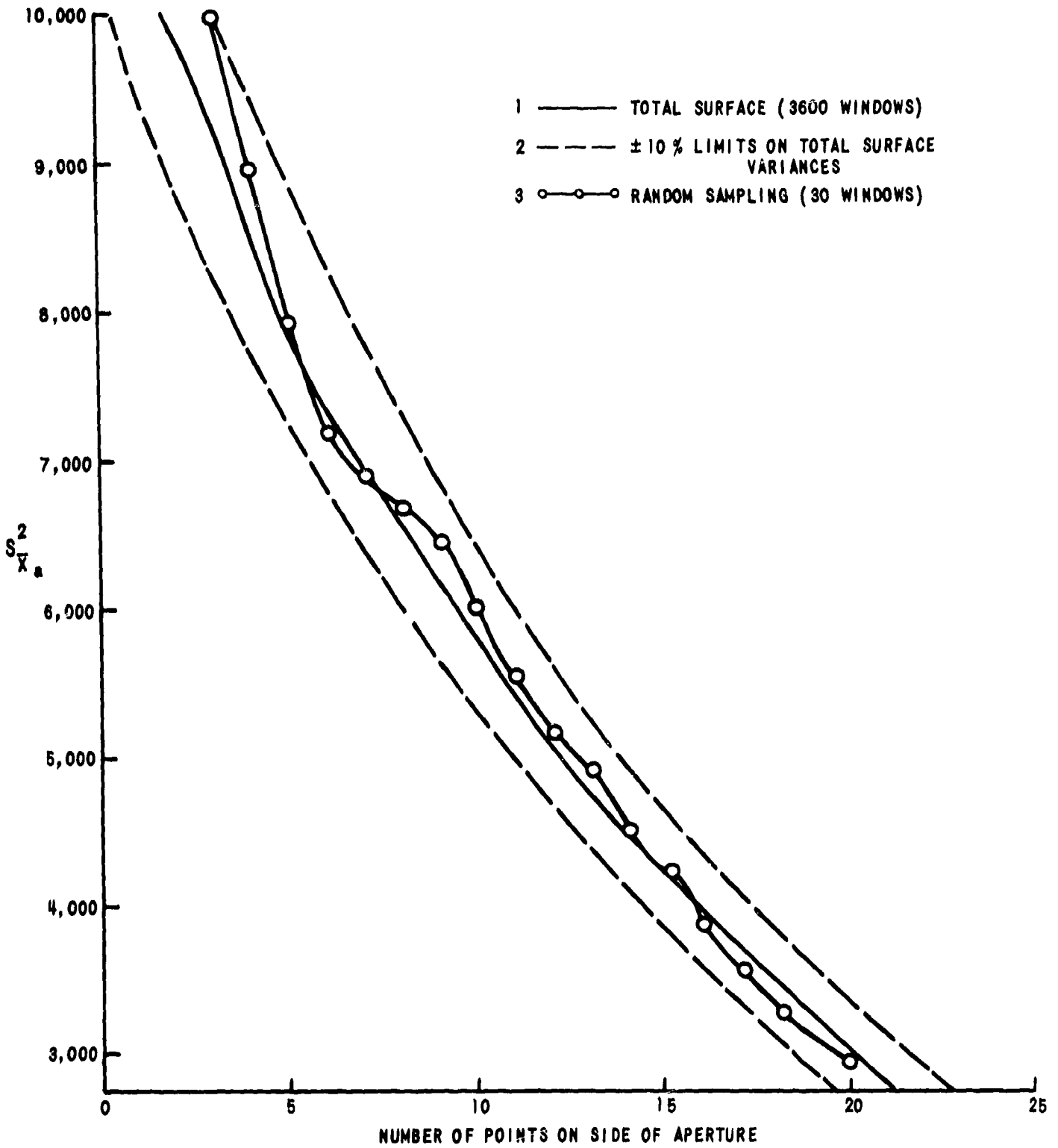


Figure C-3 VARIANCE DECAY OF TERRAIN DATA

and time limited the actual data collection to about 3000 points. The average crown size for trees in the AMPIRT study area is somewhat greater than 10 m, so it was felt that a digitization interval of 2 m would be required to measure any existing significant variations within a single crown.

Within the above constraints, the following three statistical assumptions are made:

a) In this area chosen for sampling, there is a stationary homogeneous probability density function for the values of canopy height.

b) Third and fourth moments of sample data will indicate any significant deviations from normality in the sampling procedure.

c) Complete random selection of the starting point for each window will yield a representative sample of the underlying population.

Statistical Development

It shall be assumed that the variable

$$\overline{x}_a = \sum_{i=1}^{a^2/4} x_{ai} / (a^2/4),$$

the mean canopy height within each window, will be approximately normally distributed about the true population mean with variance $\sigma^2_{\overline{x}_a}$ for values of M_a greater than or equal to 30.

$a^2/4$	=	total number of points in a window with 2 m spacing of points
i	=	index for points within a window
x_{ai}	=	a value of canopy height observed in the ith position of a window of size a^2
a	=	side of window in meters
M_a	=	number of apertures of size a^2

Also, for values of $M_a \geq 30$, the sample variance of $\overline{x}_a$ is approximately distributed as:

$$S^2_{\bar{x}_a} \sim N(\sigma^2_{\bar{x}_a}, \ \sigma^2_{\bar{x}_a}/2M_a)$$

Any serious deviations from normality should be indicated by higher sample moments. Analysis run on the German terrain data has not indicated any significant deviations, as seen in curve 3 of Figure C-3.

We are interested in $S^2_{\bar{x}_a}$, and since its distribution is known and its parameters can be estimated, we can set confidence bounds as follows:

Define:

δ = proportional confidence level

α = probability of a Type I error

z_α = standard normal z for any given α

The bound on the variance is

$$z_\alpha \sqrt{S^2_{\bar{x}_a}/2M_a} \leq \delta S^2_{\bar{x}_a}$$

$$z_\alpha \Big/ \sqrt{2M_a} \leq \delta S_{\bar{x}_a}$$

For a given α and δ we can determine M_a. The bound on the standard deviation is

$$z_\alpha \sqrt{S^2_{\bar{x}_a}/2M_a} \leq \delta S_{\bar{x}_a}$$

$$z_\alpha \Big/ \sqrt{2M_a} \leq \delta$$

This procedure has the advantage of being data independent. For α = .05 and M_a = 30, δ = .254.

This indicates that using M_a = 30, $S_{\bar{x}_a}$ will be within $\pm .254\ S_{\bar{x}_a}$ of the true population value $\sigma_{\bar{x}_a}$ 95% of the time. Using 30 windows of size 20 x 20 m, and digitizing on a 2 meter grid, the digitization process did not

exceed time or budget limitations. The actual sampling plan randomly selects 30, 20 m x 20 m windows from a 1400 x 250 m strip, allowing overlap. Figure 7 in Chapter VI shows a hypothetical distribution of 15 windows. Figure 7a indicates how 10 different window sizes are obtained from the initial 20 x 20 m window. The 20 x 20 m maximum window size should include more than one crown in most cases. It was expected that this would insure significant variance decay, which was found not to be the case.

The results of calculations on the canopy data are graphed in Figure 8.* The profile curve (lower curve) was based on measurements made at 2 m intervals along a randomly oriented line 200 m in length. The curve for the profile is seen to show a systematic decrease in variance as expected, with the variance nearing zero when the one-dimensional windows were of the order of 100 m long.

The 30 randomly chosen square sampling windows were never larger than 20 x 20 m (Figure 7). The result was that significant variance decay did not take place, as shown by the upper curve of Figure 8. The relatively higher variance exhibited between windows for the square case than for the profile is almost certainly due to the fact that different zero values were used for different square windows. The use of different zeros was necessary because the ground level is not clearly visible in the photographs and a "best guess" had to be made.

Since the profile data were digitized in about 1/30th the time taken for the square windows, and because of the arbitrary zero problem with the squares, profile measurements are probably a better use of granularity techniques than are areal data. The curves of Figure C-2 indicate that granularity provides a useful discriminant function. The simple form of the curves in Figures C-3 and 8 allows the extraction of a few parameters

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*The variance was calculated directly from parallax data, not from actual height values and thus differs from actual variance by a constant factor.

(such as coefficients in a least squares fit, or various intercept values, etc.) which could be used as characterizations of the roughness.

2. Correlation Curve Method

A curve with properties similar to the variance decay curve discussed above is obtained by considering the window averages in conjunction with the last observation within that window.

Definition

Let $h(x, y)$ and $H_i(a)$ be defined as above.

Let h_{ei} be the last observation within a window. The word last must be understood to mean a particular location in a window, and must be the same in all windows. The location should always be on the periphery of the window. For the computations reported here, the last observation has always been in the lower right hand corner for squares, or the rightmost end for profiles.

The computation of interest here is the correlation of the window average with the last observation in the window, computed over all window locations.

One would expect this correlation to decrease for larger window size, since the window average, which can, in a qualitative sense, be associated with the center, and the last observation are separated by larger and larger distances. That this is the case is shown in Figure C-4 where the correlation is plotted for 3600 windows taken from the section of German terrain previously used.

Actual forest canopy data were analyzed according to the statistical sampling plan used above in subsection 1. Correlation as a function of window size for both the thirty square windows and for the 200 m profile were shown in Figure 9. Several things are apparent from Figure 9. First, as with the variance decay, the square windows are not large enough to show significant decorrelation. The profile curve shows that the mean is decorrelated from the last observation for windows on the order of 100 m in length. This agrees with the results of variance decay in subsection 1.

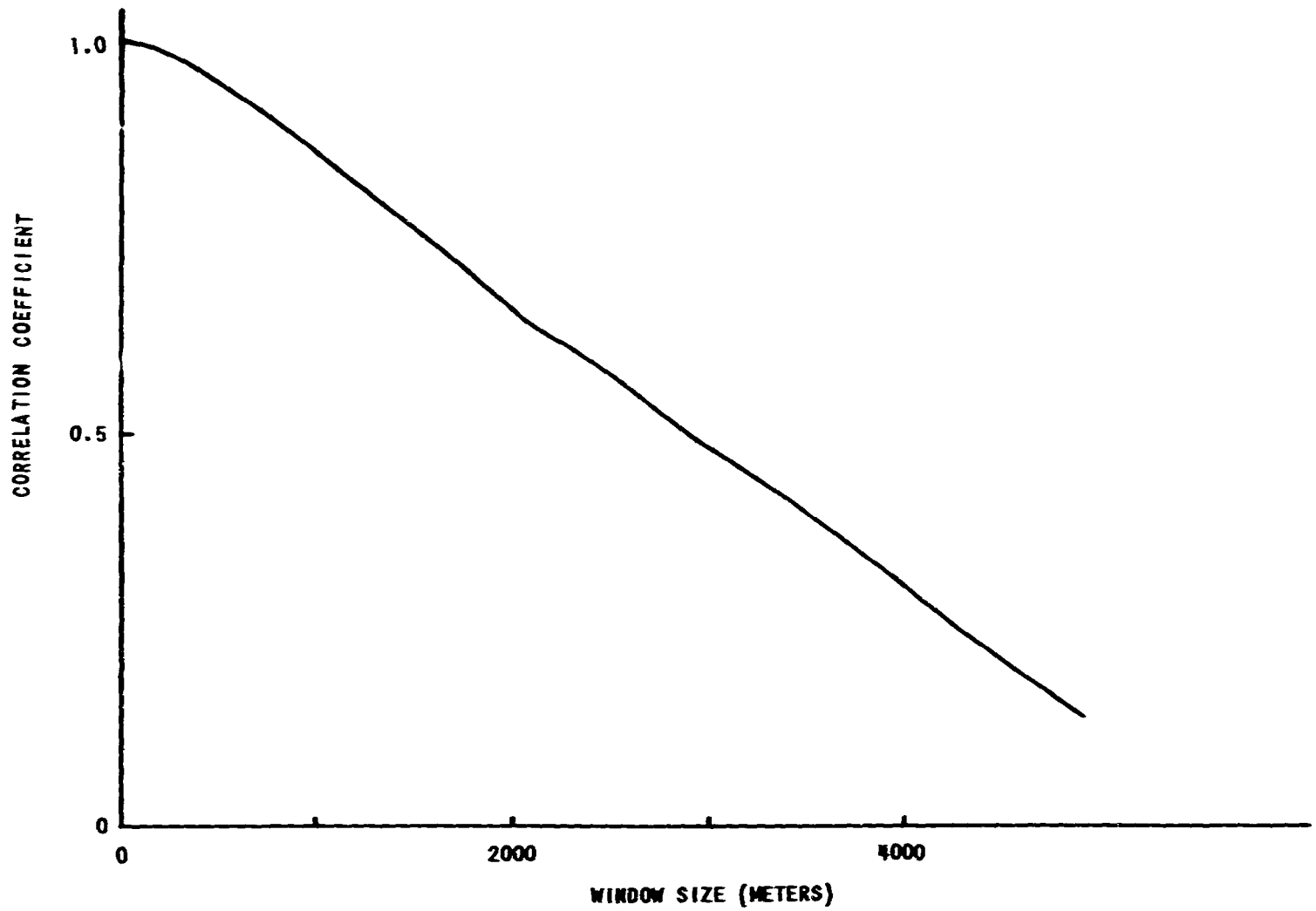

Figure C-4 CORRELATION BETWEEN WINDOW MEANS AND LAST OBSERVATION FOR ELEVATIONS OF GERMAN TERRAIN

The advantage of using a profile over the areal windows in terms of digitization time, as discussed above, holds also for the correlation curve. The problem of having a different zero for each window encountered with granularity no longer causes difficulty since the correlation of H and h_e is computed by dividing cov (H, h_e) by σ_H and σ_{h_e}. The correlation curves are relatively simple, implying that they can easily be characterized by a few parameters, as were the variance curves. The correlation curves were not examined directly for discriminant value, but because of their similarity to the variance decay curves, and because of the similarity between the two definitions, discriminant sensitivity should be about the same as in subsection 1.

B. Crossing Statistics

A second class of roughness indicators is based upon properties derived from the number of times canopy height profiles cross a horizontal line at a certain height. The analysis is simpler in both principle and application than the variance decay methods discussed above.

Definitions

These definition can be interpreted in terms of Figure C-5.

β curve: $\beta(h)$ is the fraction of the length of a straight horizontal line at height h which is below the profile. In Figure C-5

$$\beta(h) = \frac{1}{L} \sum_i \ell_i$$

μ curve: $\mu(h)$ is the number of crossings per unit length that a straight horizontal line at height h makes with the profile. In Figure C-5 this is 14/L.

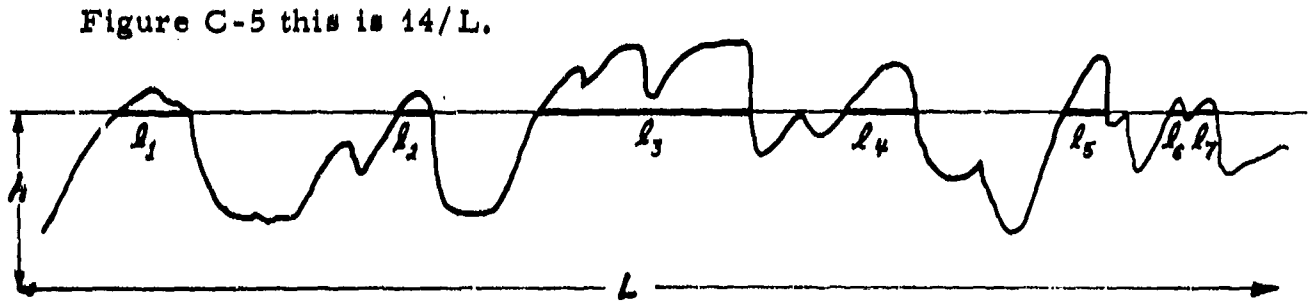

Figure C-5 INTERSECTION OF CANOPY PROFILE BY HORIZONTAL LINE USED TO DEFINE β AND μ

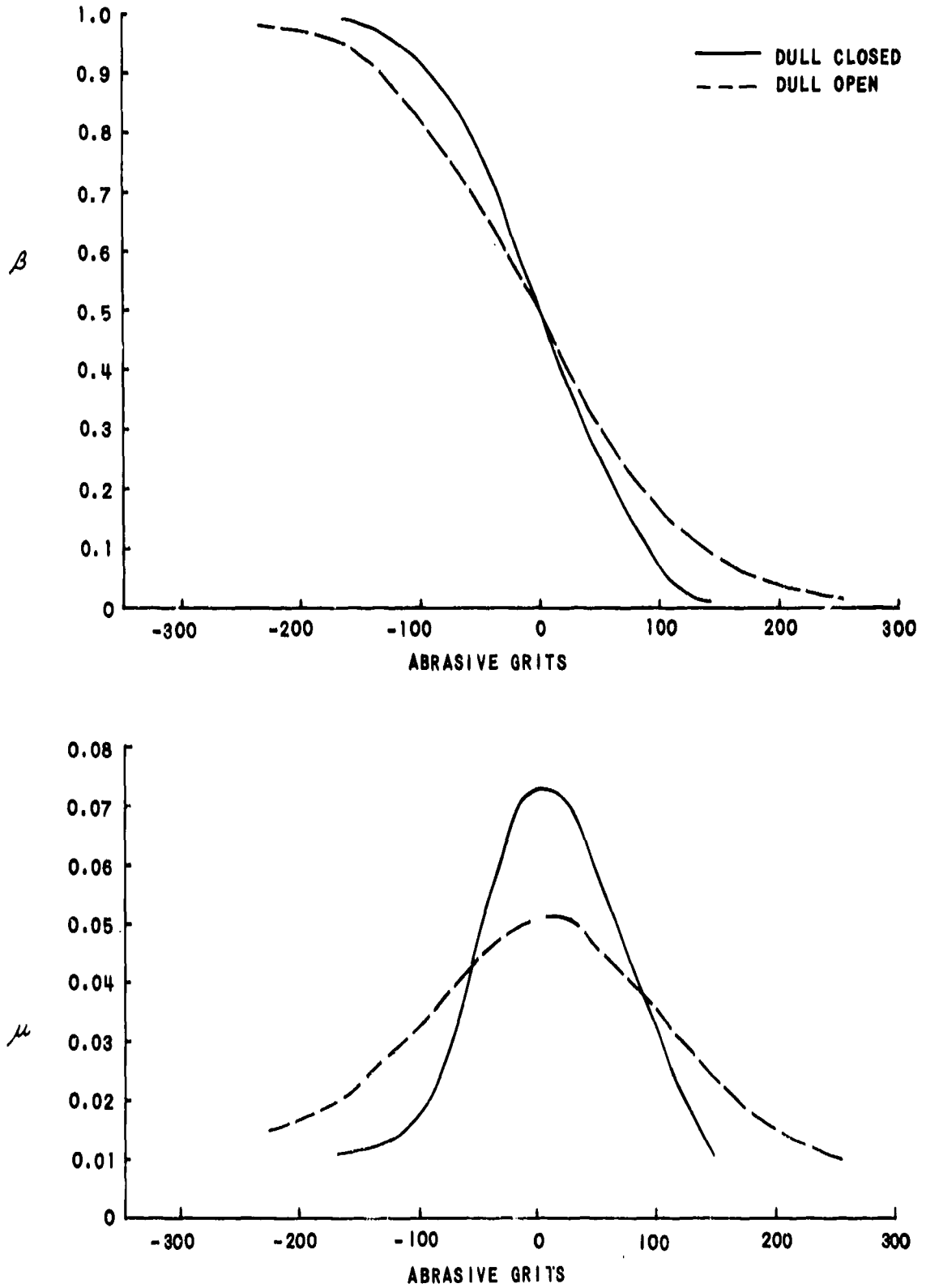

Figure C-6 EXAMPLES OF β AND μ CURVES FOR ABRASIVE GRITS

These curves were originally developed to differentiate between and characterize abrasive grit (sandpaper) in different stages of wear. That β and μ curves are capable of doing this can be seen by looking at Figure C-6. One curve in this figure is for sandpaper made from dull grit closely packed, and the other from the same kind of grits in an open arrangement. Since open and closed sandpaper configurations are more or less analogous to open and closed canopies, β and μ curves appear to be capable of meaningful discrimination.

Both a β and a μ curve are necessary to insure complete discrimination. This is demonstrated by the following examples. Consider the two profiles shown in Figure C-7a. The β and μ curves are plotted in Figure C-7b. The β curves are identical, whereas the μ curves do discriminate between the obviously different profiles. This points out the fact that frequency information is contained in the μ curve.

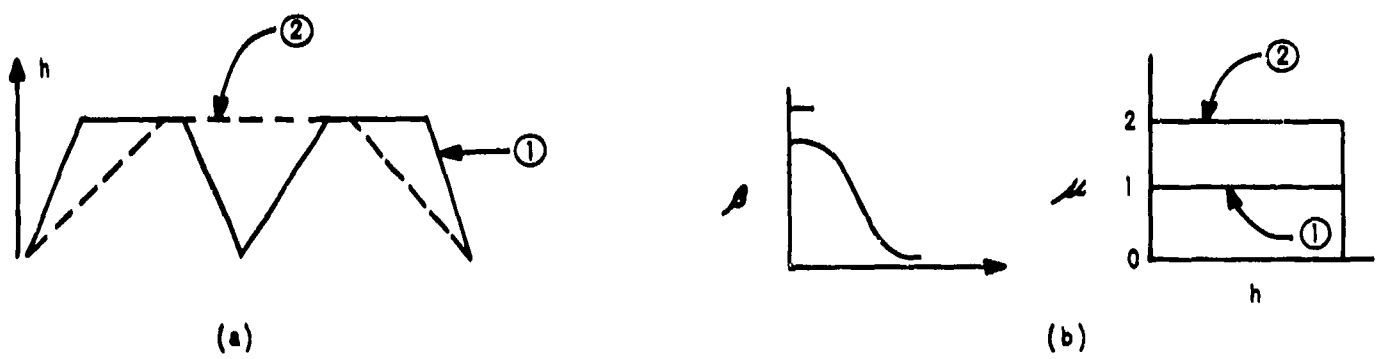

Figure C-7 EXAMPLES OF PROFILES HAVING SAME β CURVES

Figure C-8 shows an example of two profiles which have identical μ curves, but different β curves. This figure indicates that the β curve contains information about the roundedness of profiles as well as closure information.

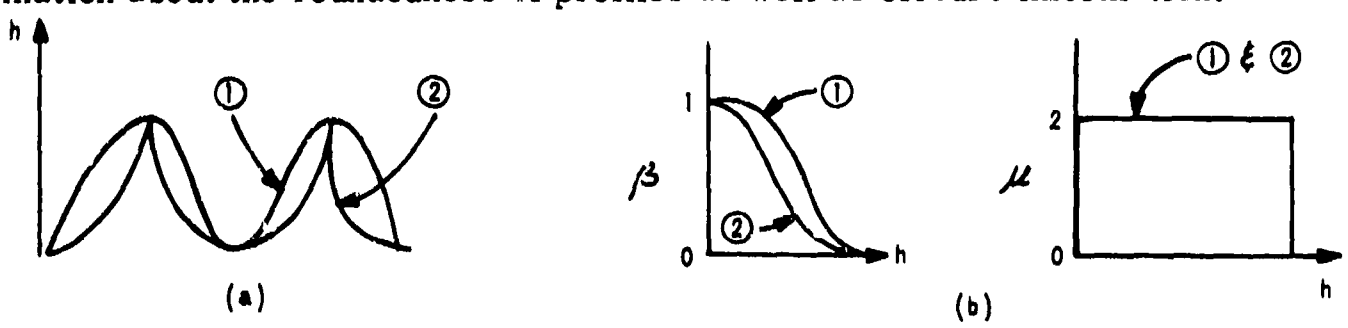

Figure C-8 EXAMPLES OF PROFILES HAVING SAME μ CURVES

The 200 m canopy profile from the AMPIRT region used above was also used here to calculate β and μ curves. The results of these calculations have been shown as Figure 10 in the text. As can be seen, the μ curve is not as smooth for the canopy profile as it was for the sandpaper, indicating the relatively less uniform structure of the canopy.

The feasibility of using β and μ curves to discriminate canopies of different roughness has been illustrated here by example. Another advantage of this methodis the possibility of applying it to data already available in the form of Richards plots.

A Richards plot applies to a forest strip usually about 10 meters wide and from 40 to 200 meters long. The plot gives both a top and side view of the vegetation sketched for the entire area. (See for example, Richards (76).)

Although a Richards plot does not give a true profile, judicious digitization should give data similar to that taken from an actual profile. Unfortunately many existing Richards plots are so short (a common size is 10 m x 40 m) that a single large tree or large hole may predominate in an area that is not really characterized by large holes or trees.

Three Richards plots were treated as profiles and digitized as an example of this application of crossing statistics. The three plots were taken from Ref. (64) and were described there as a Mangrove stand (No. 220), a Dry Evergreen stand (No. 190) and a Beech Forest (No. 104). The curves were plotted in Figure 11. Clearly, the three profiles are discriminated by the method.

It would be desirable to obtain from the crossing curves a small set of numbers that could be said to characterize a canopy. This could be accomplished if the curves were characterizable by a small set of parameters, such as coefficients of a least squares fit to a simple pair of curves. Unfortunately, it appears that the μ curves for a canopy profile will be too complex to be fit by a simple low order curve. Another method exists for grouping these (or any) curves so that each group reflects a certain range of roughness characteristics. This method requires analysis of a large number of different

canopy profiles to see if the resulting curves suggest any natural divisions. The groups thus formed could then be named and any new profiles analyzed to determine to which group they belong.

Analysis of a profile with crossing statistics can be carried further using the theory of Markov chains. Preliminary theoretical development of this scheme has been carried out, but time limits precluded any attempt to test the analysis with data.

C. Variance of Canopy Height

A single number index that may have some use as a forest canopy roughness discriminant is the variance of the total height of the top of the canopy. The variance of canopy height will discriminate between canopies with different amplitude structure, but not between different mixes of frequencies. This can be seen by considering the example below.

The variances of the three obviously different profiles in Figure C-9,

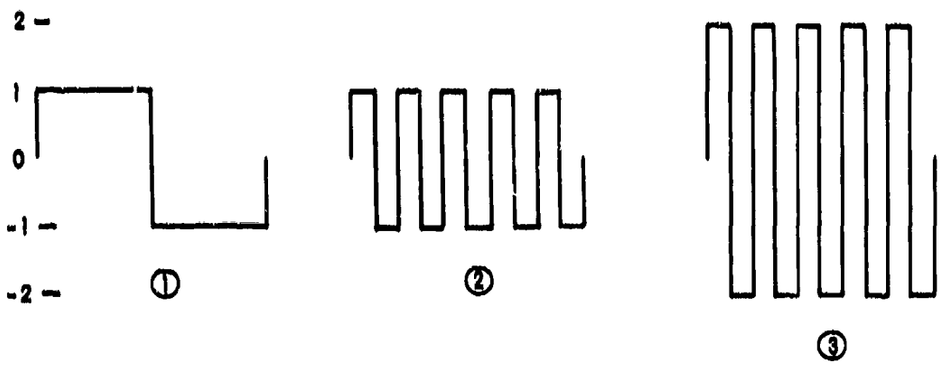

Figure C-9 SIMPLE PROFILES FOR DETERMINING VARIANCE OF HEIGHT

are shown by a simple calculation to be

Var ((1)) = 1
Var ((2)) = 1
Var ((3)) = 4

For these simple profiles it is seen that a variance of canopy height will not discriminate between profiles 1 and 2 which have the same amplitude, but different frequency, but that it will discriminate between 2 and 3 which have the same frequency but different amplitude.

Since forest canopies contain complex frequency and amplitude structure, a test program would be required to determine the usefulness of this method. Such a test program would involve calculating the variance for a number of canopies, conducting actual diffusion tests there, and seeing if the variance discriminates according to meaningful diffusion patterns. The variance of the 200 m canopy profile used for calculations above is about 21 m^2.

D. Conclusions

Four methods of characterizing forest canopy roughness and discriminating between canopies of different roughness have been presented and examined above. The feasibility of using the four methods along with some limitations has been demonstrated. Since actual forest canopy data in quantified form were not available, tests on various types of canopies have yet to be performed. The curves calculated from the AMPIRT area canopy can be used to give an indication of the magnitude of numbers to be expected from actual canopy tests.

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13. ABSTRACT

Significant features of diffusion have been delineated which are influenced by forest characterization and associated met conditions. This study outlines the vertical transport of material or momentum through the canopy and in the boundary layer above the forest and its significance. This study involved an investigation of gross forest influences that may be involved in diffusion and met measurements in a variety of forests. Data from diffusion and munition tests in forest environments were analyzed to delineate differences between forests of different physical characteristics. Above-canopy wind speeds for various forests were plotted as a function of the below-canopy wind speeds and an Environmental Index developed. The study developed techniques for characterizing the significant properties of a forest (aerosol diffusion) on the basis of relatively simple physical forest measurements, followed by a trial application of statistical approaches, using a section of forest in Thailand. Test results indicate that a method based on a measurement of canopy height made along a line can provide quantitative characterization of a forest canopy. The characterization is based on two quantities, β and μ -- both of which are expressed as functions of height above the ground. β is defined as the fraction of the length of a straight horizontal line which is below the canopy profile; μ is defined as the number of times per unit length that the line crosses the profile.

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